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East Midlands Geological Society

Correspondence

Society Secretary, 100 Main Street,
Long Whatton, Loughborough LE12 5DG
01509 843297 secretary@emgs.org.uk
Mercian Geologist Editor,
11 Selby Road, Nottingham NG2 7BP
0115 981 3833 mercian@geophotos.co.uk

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Front cover: Nottingham Castle Rock freshly exposed by removal of its blanket of ivy and shrubs; compare this with the photograph on the front cover of Mercian Geologist in 2004. Photo: Tony Waltham.

Back cover: Aftermath of the Christchurch earthquake in New Zealand (list of captions on page 283).Photos: Richard Hamblin (BGS, NERC).

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GEOBROWSER

How we got our oxygen

The focus today seems to be mainly on global climate change, particularly the link between warming of the planet and the exponential increase of atmospheric CO_2 since the start of the Industrial Revolution. But in the long run oxygen is far more important because without it animals, and therefore us, would never have evolved in the first place. A number of studies are now linking the oxygenation of our atmosphere into a complex, long-drawn-out scenario involving plate tectonics, biological evolution and chemical reactions.

Most workers agree that by the end of the Hadean Period of meteorite bombardment about 3800 million years ago, the earliest atmosphere essentially consisted of hydrogen and oxygen – in other words water vapour. Much of this fell out as rain, and virtually the whole of the Earth's surface was covered by ocean. In these waters the first life-forms evolved as anaerobic bacteria. They did not need free oxygen, but with the sun significantly cooler than it is today they played a role in keeping the planet warm by releasing methane to the atmosphere (*Science, 2002, p.1066*). In this inviting situation, the cyanobacteria began to develop. The best-known are those that form stromatolites, living today but found in rocks dated to 3500 million years old *(Nature 2006, p.714)*; the super-abundant modern microscopic organism *Prochlorococcus* has also been identified as a living ancestor of the cyanobacterium (*Nature, 2003, p.1042*). The importance of these organisms is that they photosynthesize, releasing oxygen as a waste product to the local environment. But because early oceanic waters were rich in iron, there being no oxygen to combine with elements weathered from the adjacent landmasses, all of this released oxygen was initially combined into the iron oxides magnetite and haematite; this chemical process peaked at around 2500 Ma, when particularly voluminous banded iron formations were laid down.

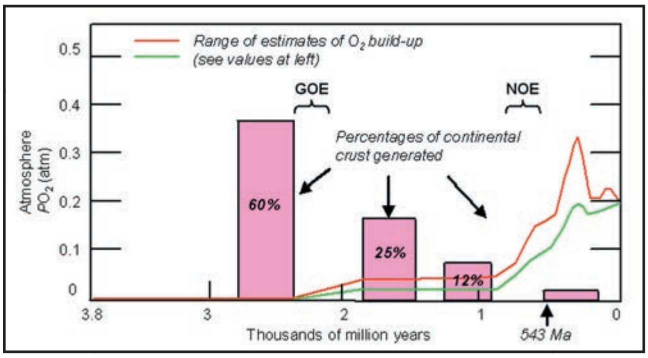
Stromatolites alive in Shark Bay, Western Australia.

Banded ironstone formation from Australia.

Plate-tectonic driver for the planet's oxygenation

Most of the major banded iron formations we see today immediately pre-date the first Great Oxygenation Event (GOE), which occurred between 2450 and 2200 Ma ago. This event is commonly attributed to the new availability in the atmosphere of photosynthetic oxygen (*Nature, 2004, p.913*); however, there was another factor, less obvious but equally important. Large tracts of shallow shelf seas were now in existence and they trapped sediment, including reduced organic carbon, thus preventing the capture of free oxygen from the water (*Nature, 2004, p. 913*). Secondly, they provided lagoonal environments for the type of cyanobacteria that make up modern stromatolites.

To form shallow seas requires the growth of landmasses and therefore of continental crust, which means that plate tectonics, rather than simple biological evolution, could be regarded as the principal underlying force driving oxygenation. This is the concept behind the theory of a Cybertectonic Earth (*J. Geol. Soc., 2007, p.*277); to some extent it opposes Lovelock's Gaia Theory (*Oxford University Press, 1979*), in which the importance of the biosphere tends to be unduly emphasized in the context of overall planetary evolution. As the graph shows, crustal growth has occurred incrementally (*J. Geol. Soc., 2010, p.229*) with the most productive phase, involving the generation of 60% of the planet's continental crust, pre-dating and thus possibly acting as one of the triggers for the Great Oxygenation Event. Following this, oxygen build-up

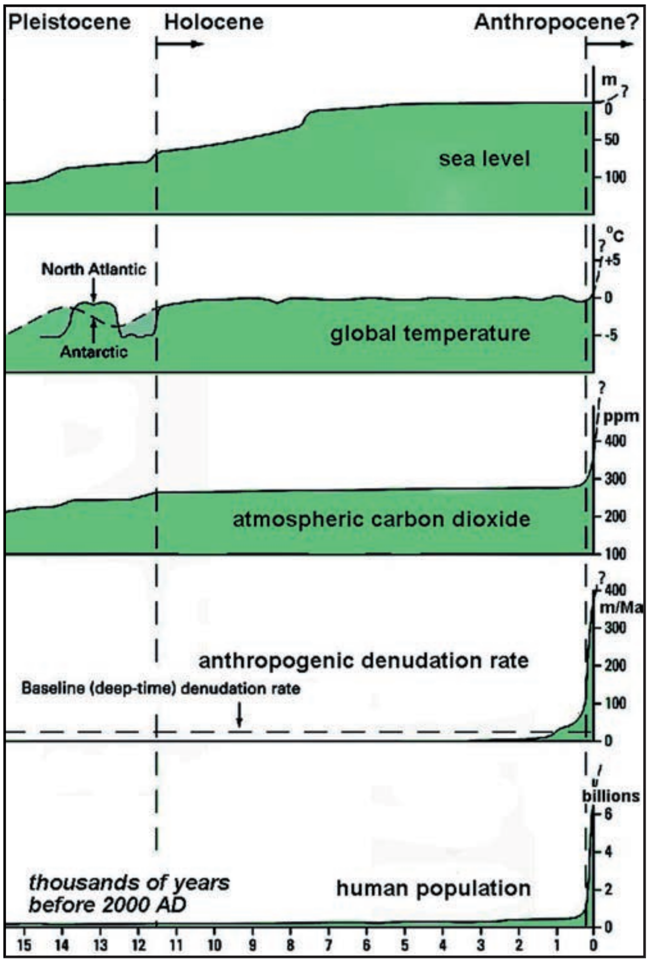


Oxygen levels correlated with continental growth.

levelled out in response to its involvement in weathering processes on the new landmasses, as well as in formation of the ozone layer. By Neoproterozoic times (600 Ma) however, these 'sinks' (to which oxygen was lost) had been largely filled and atmospheric oxygenation proceeded apace, resulting in the Neoproterozoic Oxygenation Event (NOE) (*Geol. Soc. Amer. Today, 2011, p.4*). This paved the way for the rise of animals in the final part of the Precambrian, and the explosive increase of animal life after this period had ended, 543 million years ago.

Anthropocene: a new geological epoch?

In 2000 Paul Crutzen, a Nobel-prize-winning chemist, made an off-the-cuff remark that the Holocene Epoch (the latest division of the Quaternary Period) had ended – to be replaced by the Anthropocene, in which the global environment has been changed by the effects of human development. The suggestion was taken seriously by others, and a recent publication by the Stratigraphy Commission of the Geological Society of London has discussed these effects in an attempt to ask whether such a new term can be justified by formal recognition, and if so, where and how its boundary might be placed.

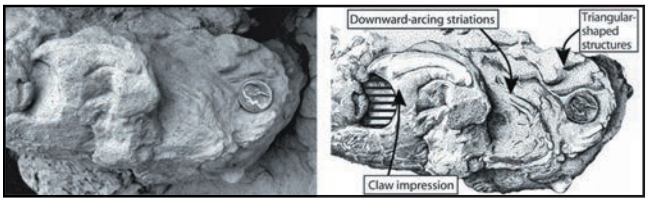


Parameters that may relate to the Anthropocene.

As yet there is no precise starting date for the Anthropocene, and until this is decided it must still be regarded as an informal term, albeit with an ever-increasing degree of usage. Certainly one could employ a number of criteria to measure and/or observe the first impacts of human development. Some suggest going back as far as 8000 years ago, when ancient farmers began to clear forests to grow crops *(Nature News, 10th December 2003*), but as the graph shows many of the more distinctive patterns we associate with human interference (e.g. atmospheric CO_2, anthropogenic denudation) would not have existed then. In a conference on the Anthropocene held at the Geological Society in London in May this year, others argued that 8000 years ago only one fifth of the planet's ice-free surface had been modified, whereas by 1750 AD not only was the Industrial Revolution starting but half of the Earth's biosphere qualified as being semi-natural and 'used'. The Stratigraphy Commission concluded that it may not be possible to set a date for the Anthropocene that would satisfy every criteria of human impact, but that a best guess around 1800 AD could be practical enough.

Digging for food: cunning dinosaurs

Perceived wisdom has it that large, lumbering dinosaurs rather stupidly laid their eggs in nests that could easily be robbed by nimble, quick-witted early mammals. With this type of scavenging, and then the meteorite impacts (*Geobrowsers passim)*, no wonder they were doomed to eventual extinction. However, features found in Late Cretaceous strata in Utah, USA, suggest that this was not always the case; before the K/T boundary extinction, dinosaurs were beginning to turn the tables on the mammals (*Geology, 2010, p.699*). In a sequence of overbank sandstones representing part of a fluvial floodplain, remarkable mega-trace fossils have been found, and interpreted as complex burrows. They commonly end in small chambers that the study compares with those made by modern rodents; but associated with the burrows are scratches and claw marks with a scale and morphology typical of a predatory dinosaur, probably a maniraptoran theropod. This study is the first to uncover dinosaur *strategies* for hunting burrowing mammals, as opposed to previous evidence of dinosaur predation such as bite marks, gut contents, coprolites and trackways.



Dinosaur trace fossil from Utah.

VALE

Alan Dawn 1923–2010

Born into a farming family near Sheffield, Alan was educated at the local school and gained a degree in geography at Sheffield University after an interruption to serve in the Royal Navy during the war. He went into teaching, with his first post in Stamford and then in Bourne. Alan Dawn was a great teacher, a gifted artist, a dedicated geologist and an enthusiastic orchid grower.

I first met Alan on a bus entering Monument Valley, Arizona. This was on the pioneering 1980 University of Nottingham geological field trip to Western USA. Alan was sitting across the aisle, and while most people were attempting to photograph though the tinted bus windows Alan was sketching. I was amazed how he could capture the essence of the mesas and buttes with a few strokes of his pencil.

The last field trip we both went on was much more recently, and was to the Isle of Eigg. Alan's legs were giving him problems so on the last stage of climbs he would sit down and take out his sketch pad until we returned. The end result was twelve views of Eigg on a calendar that was sold for a good cause.

Another chance meeting occurred at a British Orchid Society show where Alan was exhibiting. "Come to Stamford and see my collection" he said. When I did, I found him painting water-colours of geological exposures. These were preparation for the evening class that he taught. Rather than make sketches on the chalk board Alan would paint watercolours, photograph them and project the images for his students to see. I left with an orchid plant that still survives.

Although a member of the East Midlands Geological Society for many years, a regular contributor to the *Mercian Geologist*, a field trip leader and a speaker at Member's Evenings, Alan's geological legacy will be remembered through the Stamford Geological Society. He founded this thriving society with his wife Pauline, and was President for many years, inspiring so many with his hands-on, fieldwork-driven approach. With a small band of Stamford members, he was responsible for the creation of the Ketton Geological Reserve, and for the finding, excavating, recovery, conservation and presentation of numerous very large fossils, particularly ichthyosaurs, plesiosaurs and pliosaurs, from the Oxford Clay in the Peterborough brick pits. One of these projects, undertaken in conjunction with Portsmouth University, was the recovery of the enormous fish, *Leedsichthys problematicus* (Mercian, 16, 43) Another find was *Pachycostasuarus dawni*, a new species (Mercian, 14, 93). Much of the work was done at the Peterborough Museum where Alan was a volunteer and where the finds and replicas built by Alan and the group are now on display. Many of these feature backdrops painted by Alan. The group also unearthed the Deeping Elephant from Pleistocene deposits and replicated it at the Museum; one tusk was 3 m long.

Alan's work has been recognized nationally. In 1990, he became the first recipient of the Palaeontological Association's Award for Amateur Palaeontologists, and in 1994 he was awarded the Foulton Medal from the Geologists' Association. Not one to specialize, Alan's last talk to the EMGS was on Member's Evening 2008, when he talked about zeolites in Icelandic basalts. He delivered the talk with his usual aplomb while separated from the audience by a table on which there was a very large mysterious object hidden under a cloth. A true showman to the end, on completing the talk he removed the cloth to reveal the largest plesiosaur skull I have even seen. It was his latest find. As someone said: *They don't make them like that any more*.

Alan Dawn will be greatly missed, and is affectionately remembered by many.

REPORT

The Great Stretton Erratic

The Great Stretton erratic boulder was found by Rod Branson in 2008. It lies near the hamlet of Great Stretton, east of Leicester, 400 m along a footpath leading south off Gartree Road towards Gorse Lane (NGR SK64980049). The stone had been lifted out of a drainage ditch by a tenant of the Cooperative Farms.

This large erratic has not previously been recorded. It is a metabasite (metamorphosed basic igneous rock), unusual in that has not before been listed within the glacial erratics of the Midlands. It was within the Oadby till, which is generally regarded as having been deposited by an Anglian glacier moving from the north or northeast. The erratics in this till are mostly Chalk or Jurassic, derived from East Yorkshire and Lincolnshire, along with Carboniferous pebbles from northeast England and a scatter of Scandinavian rocks, including rhomb-porphyry from the Oslo area.

The boulder is elongate, about 2.12m long, 1.24 m wide and 0.8 m thick, and weighs roughly three tonnes. It is rounded with weathered surfaces. Though smooth, one of the upper surfaces shows faint glacial striations, visible only when the light is good. On the rounded edge forming the crest there is a second, later, set of striations at an acute angle to the first. These two sets of striations may have been imposed either at the source or during transport.

The erratic is dense, pale to medium bluish grey, weathering to green and brown. There is a foliated, metamorphic fabric rock, as well as patches of coarse crystals and thin seams of fine-grained material; these represent pegmatitic and aplitic phases of a pre-metamorphic igneous rock of gabbroic composition. In thin-section, the rock is roughly foliated, greenish-grey and has a granoblastic texture with relict, coarse, greyish, ragged amphibole crystals in a fine-grained matrix. There are small acicular crystals of strongly foliated and pale greenish-yellow actinolite. Adjacent to the large amphiboles are pale gren to colourless pleochroic foliated flakes of chlorite. Fine granular aggregates of clinozoisite are associated with actinolite and chlorite. Talc and white mica occur as scarce flakes, mostly in chlorite. There are also large grains of leucoxene with euhedral shape but a granular polycrystalline structure; these are probably pseudomorphs of ilmenite. Small isolated crystals of titanite are intergrown with zoisite and amphibole. Albite is very scarce and there are rare apatite prisms. The lack of plagioclase is striking, and may suggest that the original rock was a medium to coarse-grained pyroxenite of Ca-rich gabbro.

Comparison of this rock with thin sections of British and Northern European greenschist facies metabasites has revealed no exact match (John Faithfull, pers. comm.). Samples from the Auchhoad Sill, Inverneil, Loch Fyne, are fairly close in mineralogy and texture. Another similar rock occurs at Conadh Mheadtonach, Ardrishaig, Loch Fyne. The source is clearly an area of deformed greenschist facies with metamorphosed basic intrusions. Comparable rocks are present in the Norwegian Caledonides. Derivation from the Loch Fyne area of western Scotland raises problems of how the Stretton erratic was transported across the country to be enclosed in the Anglian till of the East Midlands with its north to northeast derivation, so perhaps a Norwegian source is more likely.

Another large metamorphic erratic composed of "hornblende schist" was found in the Bassingfield gravel pits between West Bridgford and Cotgrave. No detailed petrographic description has been traced, but it appears to be a similar rock type. It was transported to Nottingham University Park by Swinnerton in 1947, who described it as a hornblende schist, and it now lies half-hidden in bushes close to the lake. Legend has it used for ceremonial purposes by Bronze Age man.

Thanks are due to Rod Branson, Andy Howard (BGS), John Faithfull (Hunterian Museum, Glasgow), Andy Saunders, Trevor Ford and Roy Clements for their help and advice.

Helen Boynton

The Great Stretton erratic.

The Bassingfield erratic.

FROM THE ARCHIVES

Discovery of the Precambrian Fossils in Charnwood Forest

Down Memory Lane with Trevor Ford

In May 1957, three schoolboys, Roger Mason, Richard Blachford and Richard Allen, were rock-climbing together in an old quarry in Charnwood Forest, when Richard Blachford found a leaf-like impression on an inclined bed of fine-grained sediment; a second impression was close by. Richard pointed them out to Roger, who had taken some geology classes and realized that the impression could be an important fossil find.

He came in to Leicester to report the find at the recently established Geology Department of the then University College. I happened to be the only member of staff around, and I was rather sceptical. To back up his claim, Roger returned on May 30th with a pencil-rubbing of the rock surface, and with his father whom I knew as a part-time member of the University staff. The three of us piled into the car, and drove straight out to Charnwood, where my scepticism was soon dispelled. It was a genuine trace fossil (with no body parts), an impression of a segmented, leaf-like organism some 20 cm long, unlike any other organism, living or fossil.

I took photographs of the fossil, and a week or so later showed them to my former lecturer Peter Sylvester-Bradley at Sheffield University (he was later the first Professor of Geology at the University of Leicester). He encouraged me to write a note for the Proceedings of the Yorkshire Geological Society, of which he was the editor. Thus the pioneer paper naming the fossil *Charnia masoni* and its companion *Charniodioscus concentricus* was published in a regional journal (Proc. Yorks. Geol. Soc., 1958, v.31, p.211-217); in hindsight such an important discovery ought to have been recorded in *Nature*.

Through the good offices of Colin Sizer (Leicester City Museum Keeper of Geology), his Director, Trevor Walden, and Sir Robert Martin (Lord Lieutenant of the County), arrangements were made to extract the block bearing the two fossil impressions. Two quarrymen from Mountsorrel used chisels, hammers and crowbars to lever out a block about two metres across and 50 cm thick. As it weighed at least 200 kg, we had to borrow a lorry to get it back to Leicester Museum. Unknown to me, Colin Sizer then took the block to a local monumental mason who had a carborundum saw a metre in diameter, with the intent of cutting the large block into more manageable pieces. He brought the saw up a little too sharply, so that it shattered. And the block split, leaving the *Charnia* impression on a slab weighing about 10 kg and *Charniodiscus* on two slabs separated by a joint; they could easily be fitted together. Thus, by good luck, the two specimens became more manageable, and remain the type specimens that are still housed in Leicester City Museum.

Subsequent research has revealed that ring-like markings had been found a century earlier, in 1848, but they had been dismissed as non-fossils by Victorian experts. Also, a schoolgirl from Grantham, Tina Negus, had seen the fossil when out picking bilberries, perhaps a year before Roger and his friends went climbing in the old quarry. On telling her geography teacher about her "fossil" at Charnwood, she was summarily dismissed with "There are no fossils in Precambrian rocks": contemporary science in the raw. Tina returned to the quarry the following year, but was dismayed to find that the fossil had gone. She only entered our story after she saw Roger in a television programme about *Charnia*. In between my first and second visits, in 1957, someone else had hammered the rock around the fossil, but we never found out who was responsible. It makes me wonder how many other people had seen *Charnia* and then said nothing.

When the news broke, the Director of the Geological Survey, Sir Cyril Stubblefield, and the chief palaeontologist, Dr F W Anderson, caught the next train from London, and we took them out to Charnwood, where they were amazed that the fossil had been exposed for about a century and nobody had reported it.

Richard Blachford

Richard Allen

Roger Mason

Tina Negus

In the fifty years since my paper was published in 1958, comparable fossils have been found at several more sites in Charnwood Forest. Within only months of my original paper appearing, Professor Martin Glaessner of Adelaide, Australia, reported the discovery of comparable fossils in the Ediacara Hills, north of Adelaide. Unwittingly, I had beaten him to it by naming *Charnia* and *Charniodiscus*. A recent book was dedicated to me as "a founding father of Precambrian palaeontology".

Fossils comparable to *Charnia* have since been found in many other parts of the world, notably South Australia, Newfoundland, Russia and Namibia. I have been fortunate to visit the first two of these. The abundant late Precambrian fossils are now known from several remote localities in Newfoundland, where a nearby visitor centre attracts several thousand visitors each year. So far about a hundred species of fossil impressions have been named, mostly from rocks of comparable age, though accurate dating is not easy. An Ediacaran Division of geological time has been established to embrace the rocks now generally dated from 635 to 542 million years, i.e. latest Precambrian, also known as Neoproterozoic. This covers the period from the end of a global glaciation known as "Snowball Earth" to the beginning of the Cambrian. The ancient rocks of Charnwood Forest date from this period.

The biological affinities of the organisms which made the impressions are still controversial – are they plants or animals, or some strange in-between forms? Are they evolutionary ancestors of the fossil phyla found in Cambrian and later rocks? Or do they represent a "dead-end" phase of the evolution of life? Current opinion is that they are not ancestors of the Phanerozoic phyla, but the debate continues.

Trevor D Ford, University of Leicester

MERCIAN NEWS

Editorial

With the closing of this volume of *Mercian Geologist*, Andy Howard and Tony Morris have resigned from the Editorial Board. Both served for many years, and Andy took on the larger tasks of Editor from 1996 to 1999. The Editor and Council thank them both for their contributions to the Society. We welcome Keith Ambrose and David Bate as the new Board members.

Also with the end of the volume, the Editor places on record his thanks to Trevor Ford, Richard Shaw, Gus Gunn, Paul Lusty, Mike Rosenbaum, Tom Sharpe, Peter Fookes and Richard Hamblin for kindly reviewing submitted papers within the last four years.

In contrast with tradition, there is no index on the printed pages that close this volume. An index will shortly go on the Society's website, where it is hoped it will be more useful and accessible to the majority of researchers. Ultimately this index will become comprehensive, as new listings will be added at the end of each volume; and indices going back to the start of Volume 13 will also be added. An index for Volumes 1 to 12 was published in Volume 13.

Council has decided that the *Mercian Geologist* will continue to be published in print and distributed to all Society members and subscribers. Papers and reports in back numbers of the journal will go on the Society's website as free downloads after a date two years after their publication. The web pages at www.emgs.org.uk will therefore become the *Mercian Geologist* archive for all except the current and previous issues. We hope this will be welcomed by members and readers, and the Editor continues to invite contributions for the *Mercian Geologist* from both inside and outside the Society.

The quarrymen start work on the old quarry face to extract the block that contained the original frond and discs.

THE RECORD

Our membership now stands at 281, with an additional 32 institutional members, and we welcome the new members who have joined the Society during the year.

Indoor Meetings

As has become the custom, March saw the Annual General Meeting followed by a Members Evening. John Aram spoke of the varied geology that can be seen on the many Shetland Islands. John Jones described the geology, mineralogy and underground workings of the Golconda Mine and some of the artifacts left by miners from the 1915-1950 period. Gerry Slavin, Gerry Shaw and Brenda Slavin followed James Hutton's geological journeys in search of positive evidence to support his theory of *The System of the Earth*.

In April, Dr Haydon Bailey presented *The Forensic use of Micropalaeontology*, recounting its history and the part it played in providing evidence that led to the conviction of Ian Huntley in the Soham murder case.

In October, Howard Falcon-Long took us underground in America in search of the Carboniferous forested landscapes that have been preserved intact over huge areas.

At the November meeting we were invited to walk through time along the *Jurassic Coast* with Sam Scriven to view its geological record, see how the coast is interpreted and managed, and see the impact of its World Heritage status.

In December, Jan Zalasiewicz considered the thought-provoking subject of what the Earth would be like one hundred million years into the future and what evidence of the human race might be found there.

In January, Jonathan Lee gave us *Britain in the Freezer* with a long-term perspective of Quaternary Ice Ages including new evidence for the earlier glacial history of Britain compared to the record in other areas of northern Europe.

This year's Presidential Address in February was given by Tim Colman on the subject of *The Last 50 years of Mineral Exploration in Britain*, its problems and the change in focus in the search for different minerals during that time.

Field Meetings

The number of members participating in field meetings has again increased this year.

Our May visit was to a variety of locations in the Clitheroe area led by Neil Turner to study the origins of the Lower Carboniferous reef belt and the geological history of the area's fossils and rocks.

Our evening field trip to Bradford Dale, one of the lesser known valleys in the White Peak, in June, was led by Colin Bagshaw and Ian Sutton, as a walk to see limestone features together with examples of natural and industrial history.

As a follow up to his indoor lecture in 2008, Will Watts led a packed weekend visit in July, to the restored Rotunda museum (the subject of his talk), followed by a walk around William Smith's Scarborough and visits to locations along Yorkshire's *Dinosaur Coast* led by local geologists.

Another very popular visit to Chatsworth House was led by Ian Thomas and members of the Russell Society in October.

Keith Ambrose and John Carney led two visits to view Charnwood volcanic rocks over a weekend in September.

In October a guided underground visit to the Coal Mining Museum at Wakefield was led by Paul Guion

Council

There were five meetings of Council during the year. In continuing to support geodiversity, several members of Council have worked in the major monitoring survey that is currently underway into the condition, access and risk of RIGS in Derbyshire, Leicestershire and Nottinghamshire. The Society's Trust Fund, held to promote and support geological projects within its area, has been reviewed up-dated. Work continues on transferring the Mercian archive into digital format to make it available to a wider audience.

In conclusion I would like to thank all those I have not specifically named in my report who give much of their time and energy in order to further the aims of the Society.

We are, as always, grateful to Richard Hamblin for organizing this year's successful programme of speakers, to Gerry Slavin for co-ordinating our Members' Evening, to Gerry Shaw and his helpers for providing the refreshments, Ian Sutton for again organizing the programme of Field Trips, to the field trip leaders who so willingly give us their time and expertise, to Sue Miles for editing the Society's Circular, and to Rob Townsend for continuing to maintain and develop the Society's website.

Janet Slatter, Secretary

Notes for authors

Guidance notes for authors intending to contribute to the ***Mercian Geologist*** may be seen on, and printed from, the Society website (www.emgs.org.uk). Paper copies may also be requested by mail or by telephone from the editor for anyone without web access. Contributions are welcome from both members of the Society and non-members.

The Cressbrook Dale Lava and Litton Tuff, between Longstone and Hucklow Edges, Derbyshire

John Hunter and Richard Shaw

Abstract: With only a small exposure near the head of its eponymous dale, the Cressbrook Dale Lava is the least exposed of the major lava flows interbedded within the Carboniferous platform-carbonate succession of the Derbyshire Peak District. It underlies a large area of the limestone plateau between Longstone Edge and the Eyam and Hucklow edges. The recent closure of all of the quarries and underground mines in this area provided a stimulus to locate and compile the existing subsurface information relating to the lava-field and, supplemented by airborne geophysical survey results, to use these data to interpret the buried volcanic landscape. The same sub-surface data-set is used to interpret the spatial distribution of the overlying Litton Tuff.

Within the regional north-south crustal extension that affected central and northern Britain on the north side of the Wales-Brabant High during the early part of the Carboniferous, a province of subsiding platforms, tilt-blocks and half-grabens developed beneath a shallow continental sea. Intra-plate magmatism accompanied the lithospheric thinning, with basic igneous rocks erupting at different times from a number of small, local volcanic centres scattered across a region extending from the Midland Valley of Scotland to the Bristol and Gloucester area (Waters & Davies, 2006).

In the White Peak area of the Derbyshire Peak District, various types of igneous rocks (lavas, tuffs, sills, dykes and vents) are common within the thick sequence of Visean platform and ramp carbonates that comprise much of the distinctive, dissected limestone plateau. Data from the BGS HiRES aeromagnetic survey indicate that the outcrops of igneous rocks in the White Peak are only part of a much larger volcanic field, most of which is concealed at depth beneath Millstone Grit and Coal Measures farther east. Because no large volcano structures have been discovered so far, geological literature describes the lavas in the White Peak as probably originating from four separate centres, each being active in a different area at different times (Smith et al., 2005). These volcanic centres could have been clusters of small vents or multiple points of eruption along linear fissures, instead of individual, large volcanic massifs. Repeated flows of lava coalesced to form larger accumulations up to several tens of metres thick. Brief explosive eruptions of fine ash also escaped from smaller volcanic cones. Ash from these intermittent eruptions rained down onto the shallow sea, settling on the floor of the tropical lagoon or emergent land surfaces. Where these ash-fall sediments are preserved as recognisable layers in the limestone, they have generally decomposed to thin layers of soft clay, known as wayboards (Walkden, 1974).

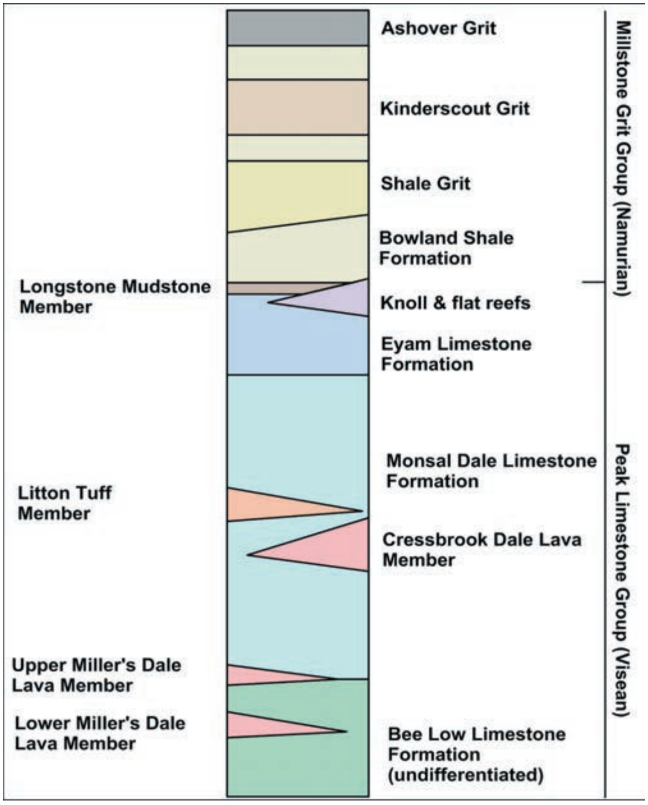


***Figure 1**. Upper Visean lithostratigraphy in the area.*

In the northern White Peak, the basaltic lavas and tuffs are interbedded with the Asbian Bee Low and the Brigantian Monsal Dale Limestones (Fig. 1). Where the igneous units form locally significant components of the carbonate succession, they are named as beds or members. Where the combined thickness of igneous rocks exceeds that of the associated limestone, they are known as the Fallgate Volcanic Formation (Aitkenhead, et al., 1985; Waters et al., 2007).

Early descriptions of the igneous rocks of the White Peak, known to the lead miners of previous centuries as *toadstone* or *channel* (Whitehurst, 1778; Farey, 1811) were followed by more detailed works (Geikie, 1897; Bemrose, 1907). Notable later publications include Walkden (1977), Walters and Ineson (1981) and the Geological Survey Memoirs (Smith et al., 1967; Stevenson & Gaunt, 1971; Aitkenhead et al., 1985). Other detailed assessments of the igneous rocks do not relate to the Cressbrook Dale Lava.

Three of the four volcanic centres in the White Peak, those at Tunstead, Matlock and Alport, have been partially eroded and their associated lava flows are

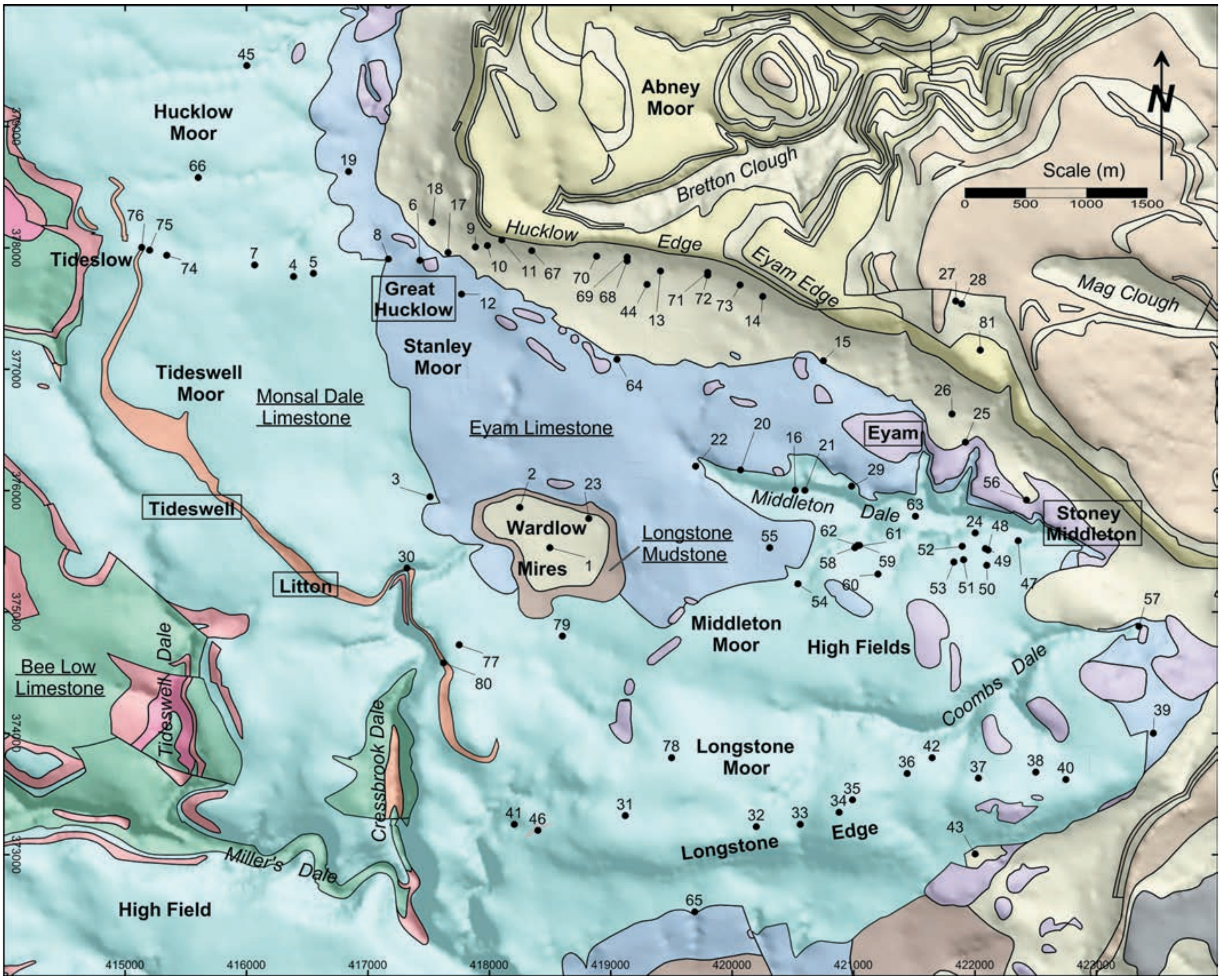


Figure 2. Outline geology of the area (relief shading after Ordnance Survey OpenData). Data locations refer to the Appendix Table. Colours are the same as in Figure 1.

exposed at surface outcrops, both natural and artificial. However, the fourth volcanic centre, located roughly beneath Eyam Edge (Fig. 2), is preserved intact, almost entirely concealed by a cover of overlying limestone, shale and gritstone. Its only surface exposure is a small outcrop close to the head of Cressbrook Dale, near Peter's Stone, and it is known as the Cressbrook Dale Lava (Aitkenhead et al., 1985). The general extent of the Cressbrook Dale Lava is known from many sub-surface intersections in old mines and boreholes spread across Middleton and Longstone Moors. Nearly all of these sites also penetrate the overlying Litton Tuff (Aitkenhead et al., 1985), a wayboard that is one of the few tuffs in the White Peak mappable as a unit.

The Monsal Dale Limestone forms much of the surface bedrock. This was deposited in a shallow sea on a sloping shelf or ramp (the Derbyshire High) that graded laterally into deeper marine environments. This limestone is generally a pale-grey, thickly-bedded biosparite and biopelsparite calcarenite. Individual bedding plane surfaces are commonly traceable over long distances, and some exhibit palaeokarstic or pressure-dissolution textures and morphology. A few beds of limestone, generally thin, not continuous, and with bivalves and corals, have been used as local marker horizons. The outcrop of the overlying, thinly-bedded Eyam Limestone, together with some associated reefs, forms a narrow fringe around the eastern side of the Monsal Dale Limestone plateau at the base of the Namurian shale and gritstone succession, though it widens in the structural depression of the Wardlow Mires basin. The older Bee Low Limestone forms the outcrop west of Tideswell Dale and Tideslow.

This area lies on the eastern side of a Variscan anticline, and most of the beds dip gently east. Towards the eastern limit of the Monsal Dale Limestone outcrop, as seen in cliffs behind Stoney Middleton, the dips are steeper where the concealed eastern margin of the platform is approached. This reef margin may trend northwest from Stoney Middleton, beneath the Namurian strata that form Abney Moor, and may be contiguous with the Castleton reef belt (Ford, 1977). The Visean limestones of the Peak District were subjected to changing stress fields during and after deposition, related to the evolving Variscan foreland

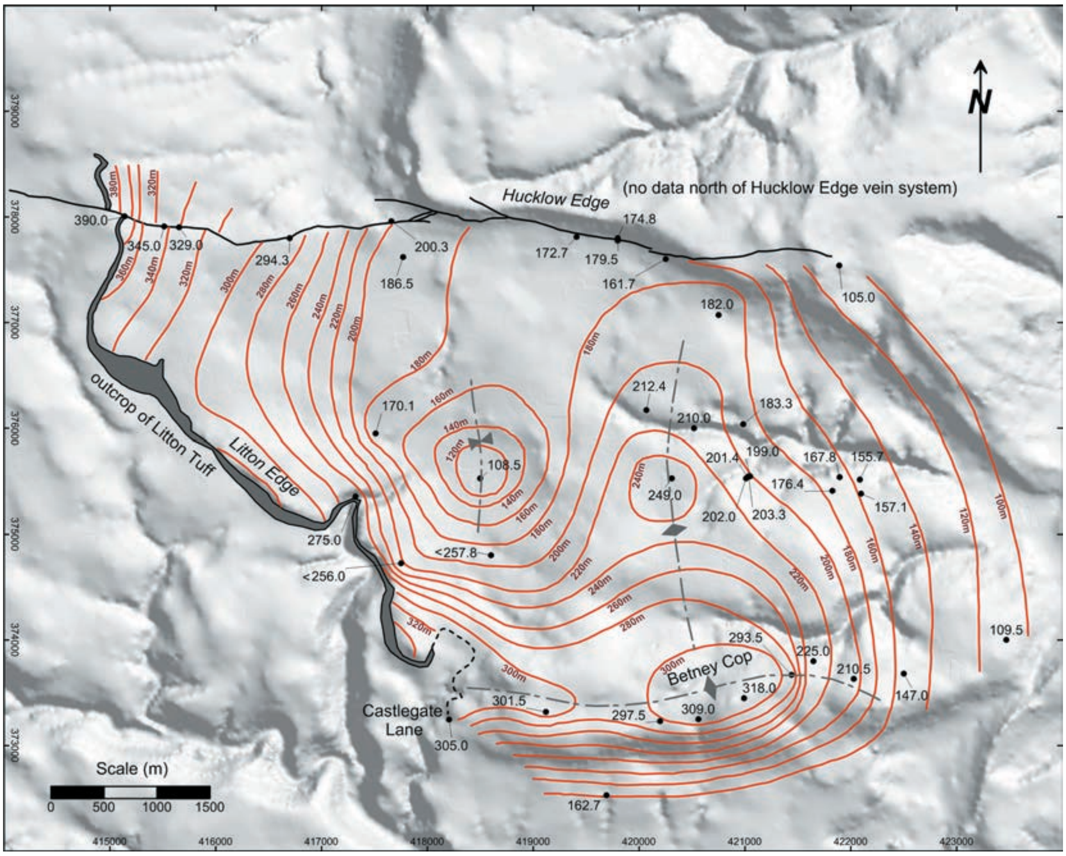


***Figure 3**. Altitudes of the top of the Litton Tuff, with structure contours drawn at 20m intervals.*

tectonics (Quirk, 1993). An early phase of extensional rifting and fracturing, controlled by NW-SE basement faults, was followed by compression and shearing, resulting in a series of regional, east-west strike-slip faults. The Visean limestone platform continued to be affected by further phases of fracturing during the late Carboniferous, following burial by Namurian and Westphalian fluvio-deltaic sediments. Many of the fractures and faults became mineralised by pulses of migrating hydrothermal fluids, mainly during the latest Westphalian and Stephanian (Plant & Jones, 1989).

The main mineral workings are clustered around Longstone Edge, Middleton Dale and the extensive Hucklow Edge vein system. The first and last of these are associated with regional east-west fault zones. The Longstone Edge escarpment is a prominent landscape feature formed by a steep, southerly-dipping monoclinal fold in the Monsal Dale Limestone beds. It is also associated with a complicated system of tensional fractures and wrench faults aligned in the same orientation, many of which have been mineralised (Hunter, 2009). Farther north, the Hucklow Edge vein system is a zone of sub-parallel, interconnecting wrench faults in the limestones; it extends for 9 km, nearly half of which is concealed beneath a cover of Namurian shales and gritstones (Hunter, 2011). Both these vein systems were mined extensively for lead ore between the 17th and 19th centuries and both supported large-scale, open-cast and underground fluorspar workings in the 20th century. Extraction of fluorspar from the Hucklow Edge vein system (Milldam Mine) ceased in 1999, while mining at Longstone Edge ended in 2010.

The distribution, thickness and general structure of both the Litton Tuff and the Cressbrook Dale Lava have been recorded between Longstone Edge and the Eyam and Hucklow Edges (Fig. 2). The shafts and boreholes that are the data sources are listed in an Appendix Table. These sources include both published and unpublished papers, reports, mine sections, borehole logs and field observations. The published documents consist mainly of British Geological Survey (BGS) Memoirs and Mineral Resource Reports, while the remainder include geological assessments conducted by quarrying and mining companies, archived historical papers and observations made by explorers of the numerous lead mines scattered across these moors. Most of the data sources are clustered in the three areas associated with the main mineral workings, Longstone Edge, Middleton Dale and Hucklow Edge.

The Litton Tuff

The Litton Tuff Member is a deposit of air-fall volcanic ash and dust mapped as a distinct bed within the Monsal Dale Limestone Formation. The western part of this bed has been removed by erosion, but the eastern part remains concealed beneath 50-60m of limestone (Fig. 3). Its outcrop extends over at least 6 km around the villages of Litton and Tideswell, where the weathered, clayey material is soft and is usually obscured beneath a layer of soil and thick turf. At its southern end, the tuff is very thin and has not been traced as a mappable unit, but a temporary exposure in 2004 revealed it in a shallow mineral working near Castlegate Lane (Fig. 4).

***Figure 4**. Temporary exposure of the Litton Tuff (grey and yellow clay) overlain by the Monsal Dale Limestone at Castlegate Lane in 2004; section is 3m high.*

The Litton Tuff was also intersected by the Sallet Hole Mine between the eastern adit entrance in Coombs Dale and the newer decline at the western end of Longstone Edge, at Watersaw Rake (Fig. 5). These underground exposures (no longer accessible) showed that the Litton Tuff can occur as two or more leaves of pyroclastic material separated by thin beds of limestone.

The structural contours (Fig. 3) define large-scale undulations superimposed upon the regional dip to the east; these contours depict only generalised surfaces and include some uncertainty. The tuff is conformable with the bedding of the limestone, so these contours also indicate the structure of the upper Monsal Dale Limestone. The synclinal Wardlow Mires Basin and an unnamed anticline lie north of a domed, east-west anticline aligned with the Longstone Edge monocline beneath the higher ground of Betney Cop. These gentle undulations have been described as folds formed by Variscan deformation (Stevenson & Gaunt, 1971), but there may be an alternative explanation (see below).

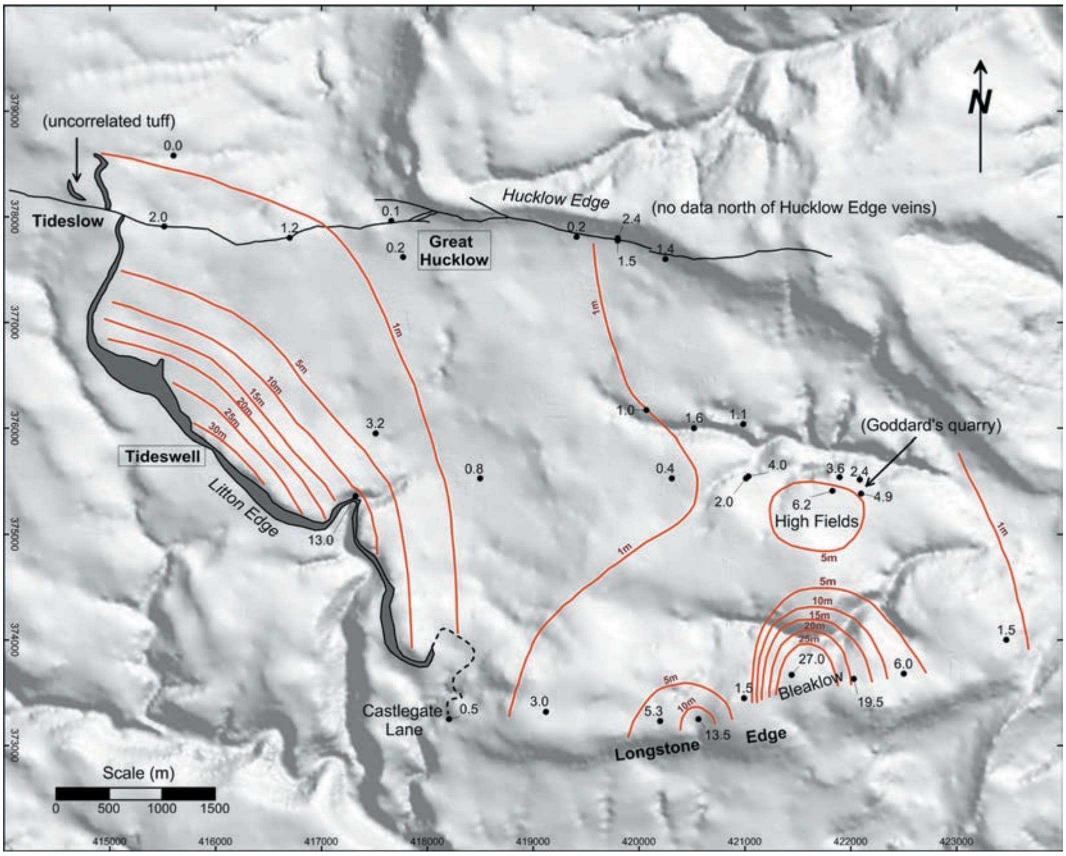
***Figure 5**. Thin layers of Litton Tuff within the Monsal Dale Limestone, in underground workings beneath Longstone Edge, 2008; section is 1.5m high.*

The sinistral fault movement associated with the Hucklow Edge vein system has created a vertical offset of the eastwards-dipping strata across the fault. There are insufficient data points from north of the fault to determine structure. Sinistral fault displacement on the Longstone Edge vein system has also created a minor, vertical offset of the strata on its northern side (but this is too small to plot and has been ignored). Horizontal slickensides are common in the mineral workings of both vein systems. The horizontal displacement on the Longstone Edge fault system can be estimated where the two halves of the Betney Cop domal structure are offset by about 130m (Hunter, 2009).

It is evident from the thicknesses of the Litton Tuff that it represents the combined ash-fall footprint from at least two volcanic vents (Fig. 6). One lies west of Tideswell, and the other is buried beneath Bleaklow, on Longstone Edge. A third, minor vent may exist west of Bleaklow, and a fourth may possibly occur in the vicinity of High Fields. Observations in underground workings beneath Longstone Edge of more than one leaf of the Litton Tuff (thicker than those in Figure 5 and separated by thin beds of limestone) suggest that the multiple vents produced sequential eruptions. The ash-fall from the Tideswell source appears to have spread over a wider area than that from the Bleaklow vent, though it thins rapidly from over 30m to under 1m across a distance of 2 km. Some of the thinner recorded intersections of the Litton Tuff, particularly beneath Hucklow Edge, may not be reliable because they could relate to thin wayboards at slightly different stratigraphical levels. At least two wayboards were recorded in 19th century sections of mines between Great Hucklow and Tideslow. One of these could be associated with a second outcrop of unnamed tuff north of Tideslow (Hunter, 2011).

The 5m contour lines shown in the eastern half on Figure 6 could be re-drawn differently to connect the Bleaklow and High Fields areas into a single tuff deposit elongated north-south. Both options are feasible using the data points, but the drawn contour lines are preferred since the discovery in 2009 of a grey, clayey tuff during limestone production at Goddard's Quarry, on the north side of High Fields. This additional tuff is not plotted on Figure 6. Although it appears to be stratigraphically higher than the Litton Tuff, which was located by pre-development drilling around the quarry, it hints at the existence of a local, small volcanic vent that may have been reactivated. The discovery of tuff,

Figure 6. Thicknesses of the Litton Tuff, indicated by isopachytes drawn at 5m intervals.



where limestone was expected, was one factor behind the early closure of this quarry. A possible volcanic centre near High Fields may also relate to local reversals of dip in the overlying limestone along the north side of Coombs Dale on a plateau where the predominant dip is north and northeast.

The Cressbrook Dale Lava

Though this lava is known to be a significant component of the Monsal Dale Limestone sequence beneath much of the area, its outcrop is limited to a thin exposure of dark, vesicular basalt near the head of Cressbrook Dale (Fig. 7). It lies below the Litton Tuff, at depths beneath the plateau surface ranging from 28m, where the anticline ridge crosses beneath Middleton Dale, to around 100m beneath much of Longstone Edge, and 180m at the eastern end. Consequently, it has been intersected by fewer boreholes and mine shafts than have penetrated the Litton Tuff. Even fewer boreholes have penetrated completely through the lava. Figure 8 shows structural contours on the lava, and also its probable western limit within the limestone.

Along the Hucklow Edge vein system, more elevations of the upper surface of the Cressbrook Dale Lava are known that exist for the Litton Tuff, because the lava toadstone was readily recognised in the mines and boreholes, whereas the Litton Tuff is so thin it would have been difficult to identify with certainty. The undulations in the upper surface of the lava are comparable to those of the Litton Tuff (Fig. 3) because they are associated with the same regional dip and the same folds. However, these two surfaces are not parallel

Figure 7. Outcrops of the Cressbrook Dale Lava (CDL) and Litton Tuff (LT) in northern Cressbrook Dale.

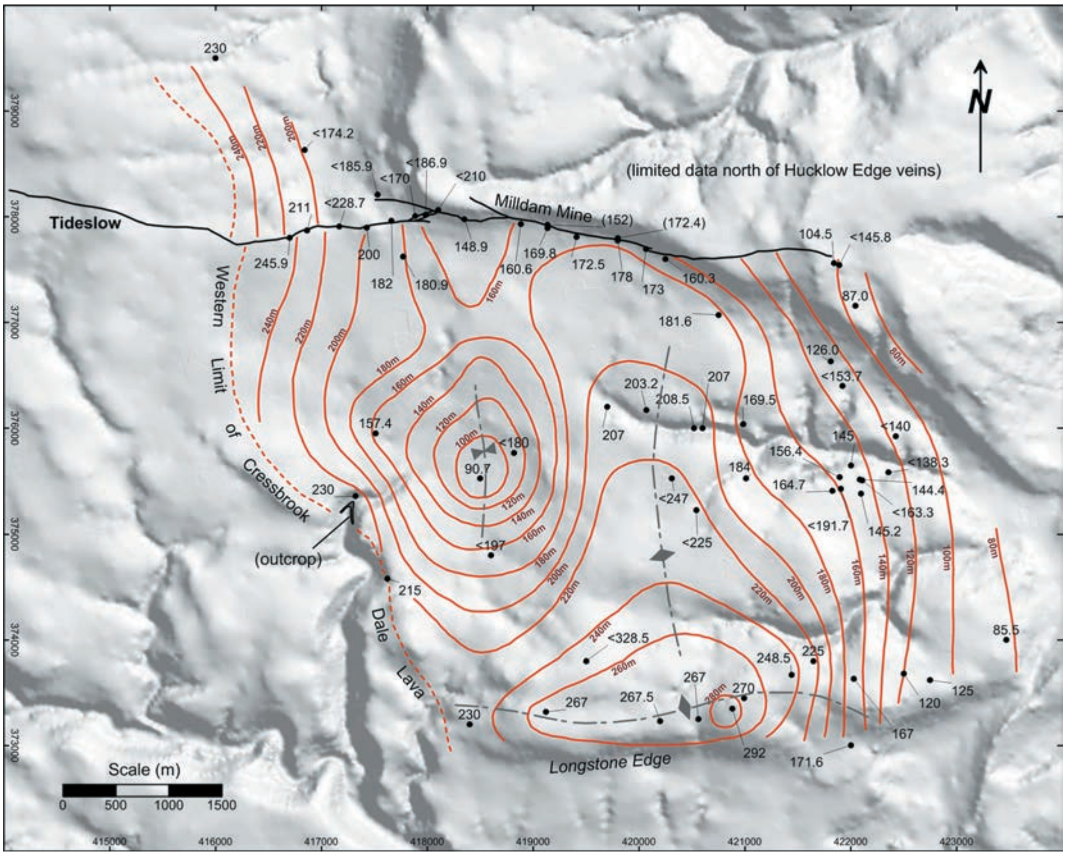


Figure 8. Altitudes of the top of the Cressbrook Dale Lava, with structural contours at 20m intervals.

to each other; they converge in a north-easterly direction from Longstone Edge and Litton Edge towards Eyam-Hucklow Edge. This convergence indicates that a local sea-floor relief of up to 50m had been infilled and possibly levelled when the air-fall Litton Tuff fell into the sea (Fig. 9). Cyclic changes in relative sea level, due to local tectonics and the late-Visean glacio-eustacy, may have caused repeated drowning and re-emergence of the flanks of the volcanic terrain. As a consequence, the contact between the lava and its limestone cover is likely to be interbedded and more complicated than this simplistic model implies. The conical mounds of ash that accumulated around the Litton Tuff vents would have formed new features on the sea floor.

Lithological logs for the boreholes located along the Eyam-Hucklow Edge usually show a thin layer of tuff lying directly on the upper surface of the Cressbrook Dale Lava. This thin tuff probably correlates with the Litton Tuff in the Wardlow Mires No.1 borehole (Stevenson & Gaunt, 1971). Uncertainty is created by the wide spacing between the data points, but it is reasonable to assume by extrapolation that the horizon of the Litton Tuff lies very close to, and possibly coincides with, the eroded upper surface of the Cressbrook Dale Lava beneath the Eyam-Hucklow Edge.

In common with many of the rake-vein lead mines of the White Peak, the veins mined beneath Hucklow Edge deteriorated in width and quality as they passed downwards from the limestone into the igneous rock. The upper surface of the lava, which is usually altered to a clay, also behaves as an aquiclude, and drainage problems were commonly encountered in the deeper mines as they approached this hydrogeological barrier. In the modern Milldam fluorspar mine, which extracted gangue minerals left behind by the 18th and 19th century lead miners, the location of the upper surface of the lava was determined by underground drilling prior to the development of new levels, declines and stopes. Subsequent tunnelling was positioned to avoid intersections with the lava because its uppermost layer would soften and degrade following exposure to air and water, causing operational problems in the mine and the mill.

Two pairs of underground drill holes from Milldam Mine enable the vertical fault-offset across the Hucklow Edge vein system to be measured (elevations of the upper surface of the lava on the northern, down-thrown side are in brackets on Figure 8). Further west along this vein system, towards Tideslow, some old mine workings recorded the upper surface of the lava on the northern side of the fault, but the recorded elevations do not identify on which side of the fault they are located. Consequently, it is not possible to extend the structural contours very far on the northern side of the vein system. Another underground borehole from Milldam Mine has recorded a deeper intersection (148.9m AOD) with the upper surface of the lava than the adjacent known elevations on either side of it. This could indicate a northerly extension of the Wardlow Mires basin into a valley in the upper surface of the lava, but is depicted on Figure 8 as a separate, northerly-facing depression; its significance is discussed below.

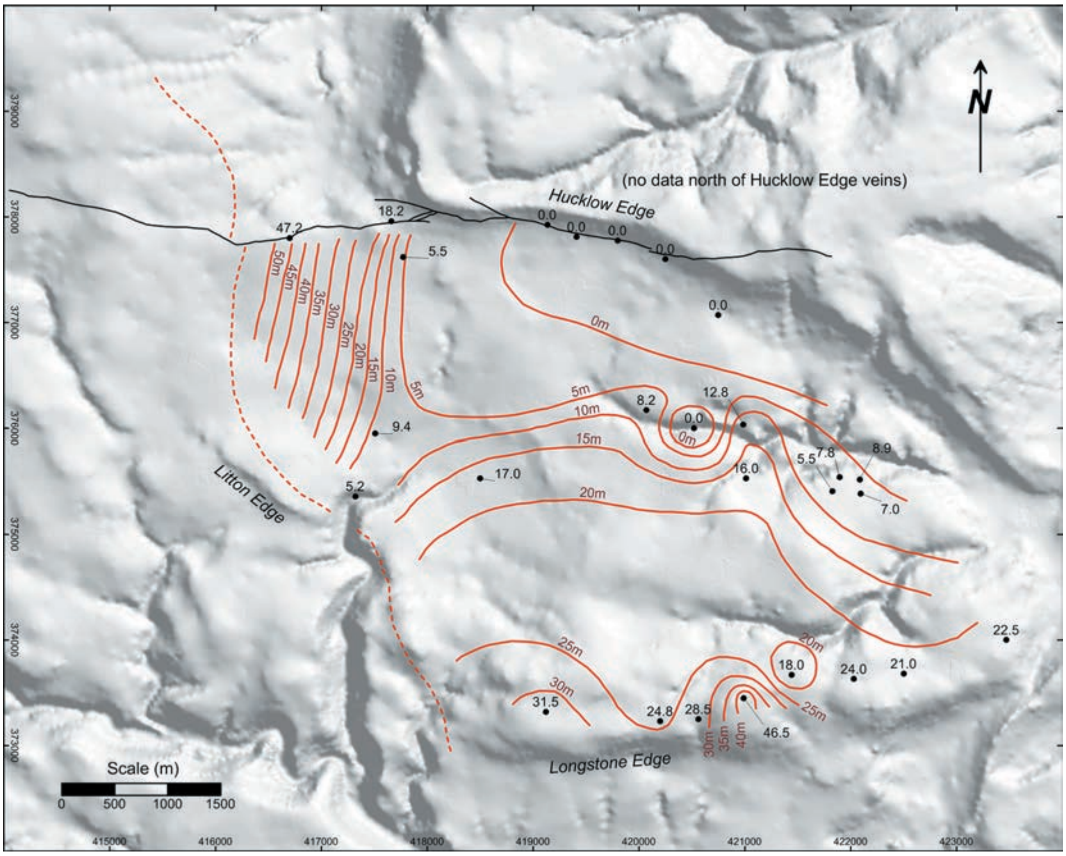


***Figure 9**. Thicknesses of limestone separating the Litton Tuff and the Cressbrook Dale Lava, with isopachytes drawn at 5m intervals.*

Some of the old drill cores from Milldam Mine show the contact of the Cressbrook Dale Lava with the limestone above(Fig. 10). The layer of decomposed tuff, now reduced to clayey, grey dust, is the same unit, possibly the Litton Tuff, that is shown in contact with the upper surface of the lava in lithological logs for most of the other Eyam-Hucklow Edge boreholes. Bleaching of the upper 2-3m of the Cressbrook Dale Lava is evident in all of the Milldam cores that were examined. The bleaching may represent weathering of an emergent land surface before it was smothered in volcanic ash, or it may have been the result of alteration caused by the ash. It is likely that the lava surface was already submerged beneath the wave-base at the time of the ash-fall, or the tuff would not have been preserved.

The thickest accumulation of the Cressbrook Dale Lava occurs beneath the area between Eyam and Foolow, becoming thinner towards the west and south and eventually terminating on its western side approximately beneath Litton Edge (Fig. 11). The lava is usually described from borehole cores as a dark grey-green, fine-grained, olivine basalt with both massive and amygdaloidal textures. A thick sequence of auto-

***Figure 10**. Drill core that penetrated tuffs, possibly the Litton Tuff, and through the upper surface of the Cressbrook Dale Lava, from borehole 22/91 in Milldam Mine. Top left is pale limestone (at the stratigraphic top), followed by decomposed tuff to its right; the bleached and altered upper zone of the lava is in the two middle rows; unaltered, dark, amygdaloidal lava is in the lowest line; scale rule is 15 cm long.*

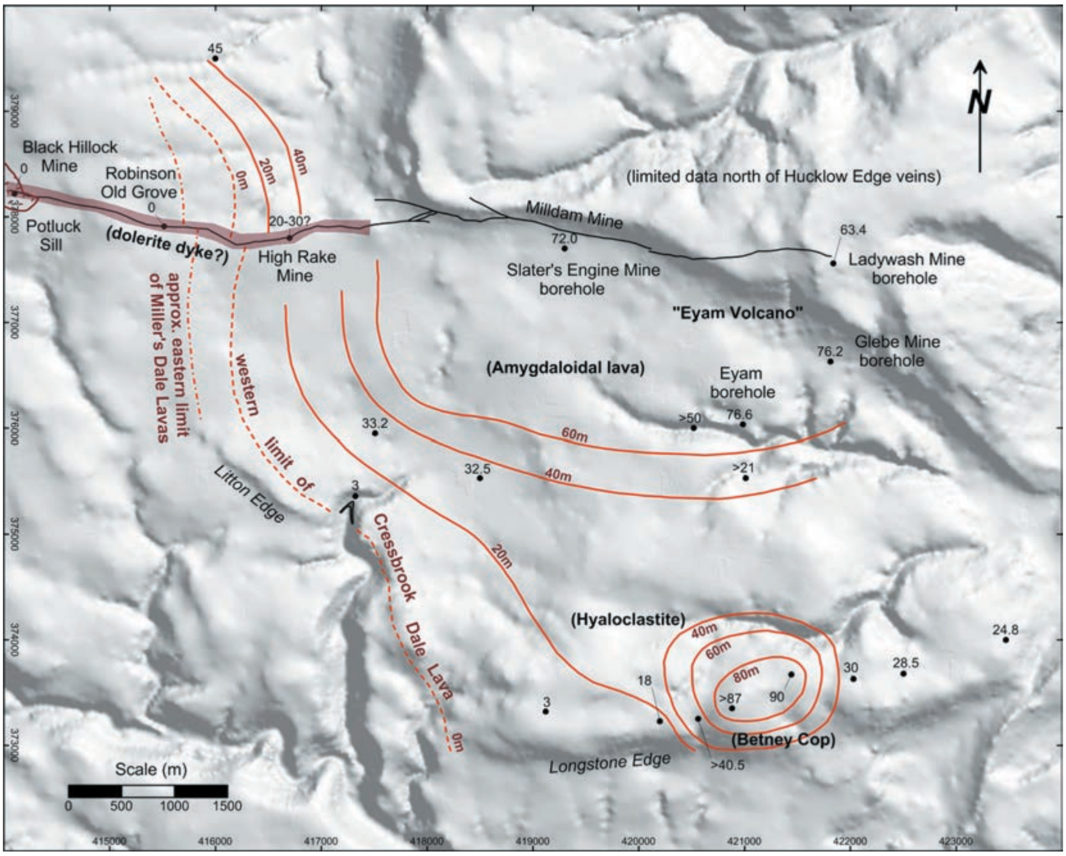


***Figure 11**. Thicknesses of the Cressbrook Dale Lava, with isopachytes drawn at 20m intervals.*

brecciated lava lies in the lower part of the unit in the Wardlow Mires No.1 and Eyam boreholes (Walters & Ineson, 1981). The shape, dimensions and location of this large volcanic mass seem sufficient to justify applying the name *Eyam Volcano*. A separate volcanic mound, of similar thickness but smaller lateral extent occurs beneath Betney Cop, on Longstone Edge. Its extent has been partly delineated by a series of boreholes and it is described as hyaloclastite and tuff (Aitkenhead et al., 1985), implying that this localised volcanic vent only erupted underwater and did not create an island with sub-aerial lava flows. The hyaloclastite ie exposed in Sallet Hole Mine (Fig. 12). Walters and Ineson (1981) considered the Longstone Edge volcanics as a separate and possibly older eruption than the main Cressbrook Dale Lava, but Aitkenhead et al. (1985) correlated the two igneous units and regarded them as different components of the same volcanic event. Using the Longstone Edge boreholes the same authors also identified another thin lava below the Cressbrook Dale Lava, but they described it as a northerly extension of the older Shacklow Wood Lava, derived from the Alport volcanic centre. The lava outcrop above the River Wye at Cressbrook Mill is considered to be part of the Upper Miller's Dale Lava (Gatliff, (1982).

***Figure 12**. Bedded hyaloclastite (pale grey) exposed underground in Sallet Hole Mine, Longstone Edge in 2005; section is about 1.5m high.*

Several intrusive sills of olivine-dolerite crop out to the west. One of these, the Potluck Sill, partly intrudes into the Lower Miller's Dale Lava, demonstrating that it is younger than that eruption. Between the 1760s and 1790s, Black Hillock Mine (Fig. 11) was sunk into a narrow mineral vein associated with the faulted contact between the lava and the sill (Walters, 1980). The miners were expecting to penetrate through the toadstone to investigate the anticipated continuation (and enlargement) of the mineral vein in the limestone beneath. Unfortunately for the investors in this unlucky venture, the shaft was abandoned while probably still in igneous rock (the historical accounts are not entirely clear about this) at a depth of 220m, because of increased water inflows and the lack of any evidence of ore. It is likely that the shaft penetrated at least 94 fathoms, ~180m, of toadstone. Farther east, a similar result befell High Rake Mine in the 1840s (Hunter, 2011). This shaft encountered the upper surface of the toadstone at a depth of 84m below ground, but the miners were still in igneous rock when it was abandoned at a depth of 216m, indicating a thickness of at least 132m. Both these mines are in the Hucklow Rake vein system. No other mine along the same vein ever managed to penetrate through the toadstone, though none was as deep as the Black Hillock and High Rake mines.

Both the Lower and Upper Miller's Dale Lavas have concealed extensions east of the Potluck Sill, but these do not extend as far as High Rake Mine (Gatliff, 1982), and gradually become thinner as they approach their distal limits. Therefore neither the Miller's Dale Lavas nor the Cressbrook Dale Lava have sufficient thickness in this area to account for the *bottomless toadstone*. Loose rock in the archaeologically important hillocks at High Rake Mine indicates that at least some of the toadstone was amygdaloidal lava, confirming the description by Green et al. (1887). Therefore it seems likely that the Cressbrook Dale Lava was the first igneous rock encountered during shaft sinking, where it may have represented the uppermost 20-30m of toadstone. Green et al. (1887) do not state the depth to which the lava extended nor the nature of its contacts.

Previous attempts to explain the abnormal thickness of igneous rock encountered by these mine shafts have proposed that they were sunk into vertical volcanic feeder pipes or into a thick, concealed intrusive sill (Walters, 1980; Walters & Ineson, 1981; Rieuwerts, 2007). The first theory assumes that the Potluck Sill is associated with, and directly above, a vertical volcanic feeder pipe. This cannot be disproved, but it invokes a coincidence that the High Rake shaft was also sunk into a separate feeder pipe 2.6 km away. Such feeder pipes would need to be either sufficiently large or uniformly vertical so that the mine shafts did not break out through their sides. The second theory, of a thick intrusive body underlying a wide area from Great Hucklow to Tideslow, also cannot be disproved, but the absence of any identifiable magnetic anomaly (see below) opens this concept to doubt.

An alternative model proposes that the deep mine shafts along Hucklow Rake may have both been sunk into a concealed vertical dyke extending westwards from the Eyam Volcano to the Potluck Sill (Hunter, 2011). Its relationship to a parent volcanic plug could be similar to the radial dykes around the eroded Tertiary volcano at Shiprock, New Mexico, USA. One of only three known examples of probable dolerite dykes in the northern White Peak crops out west of the Potluck Sill (Stevenson & Gaunt, 1971). Though only known from soil auger samples, it is linear and narrow and appears to connect the Potluck Sill with the Mount Pleasant Sill a few hundred metres further west. Its mapped orientation aligns with the projected end of the proposed dyke beneath the Hucklow Rake vein system, and it could represent a distal extension.

The concept of a deeper, concealed dyke may be supported by the structure of the Monsal Dale Limestone that overlies it. The position of the proposed dyke is marked by an east-west ridge of high ground connecting Hucklow Edge with Tideslow. It forms part of the surface drainage divide between catchments draining north towards the River Noe and south to the River Wye. Like the land surface, the limestone dips away from the ridge on both sides. These opposing dips could have been initiated by flexing of the limestone beds across the rigid dyke during burial settlement, allowing tension fractures to develop along the hinge. Subsequently, Variscan east-west wrench faulting exploited the weakened fracture zone, enlarging some of the fractures and allowing a major system of hydrothermal mineral veins to develop. Evidence supporting the concealed dyke hypothesis is limited and circumstantial, though no more so than the alternative explanation of multiple volcanic vents conveniently aligned beneath the Hucklow Edge vein system.

The magnetic anomalies

In 1998 a high-resolution airborne geophysical survey was commissioned by the BGS to cover an area of 14,000 km^2 of the English Midlands, including the Peak District (Shaw, 2005). A magnetic gradiometer was one of the standard instruments carried by the aircraft. To reveal additional details about the concealed Cressbrook Dale Lava, the original values of magnetic flux density have been manually re-contoured to intervals of 5 nanotesla (Fig. 13).

Magnetic anomalies are identified by letters on Figure 13. Most prominent is the large, positive anomaly (A) cresting near Crosslow House, north of the road between Eyam and Foolow. The entire anomaly defined by the 15 nt contour extends along the southern scarp of Eyam-Hucklow Edge, from Stoney Middleton to beyond Foolow. It includes a second anomaly peak (B), while a third magnetic maximum (C) forms a separate but adjacent anomaly on Stanley Moor. All three of these magnetic peaks lie within the 60m lava isopachyte (Fig. 11), and it seems reasonable to associate this A-B-C magnetic anomaly with the thickest accumulation of lava associated with the proposed Eyam Volcano. The complete contours of this anomaly may also enclose the other half of the Eyam Volcano at depth north and east of Eyam-Hucklow Edge. The volcanic mass appears to extend as far north as the Abney Syncline (near Bretton Clough) and eastwards towards the River Derwent, as predicted by Walters and Ineson (1981).

The steeply-dipping, eastern reef-margin of the Visean carbonate platform has been intersected by two crosscuts east and north from the Glebe and Ladywash mines (J. Beck, pers. comm.) (Fig. 13). The platform

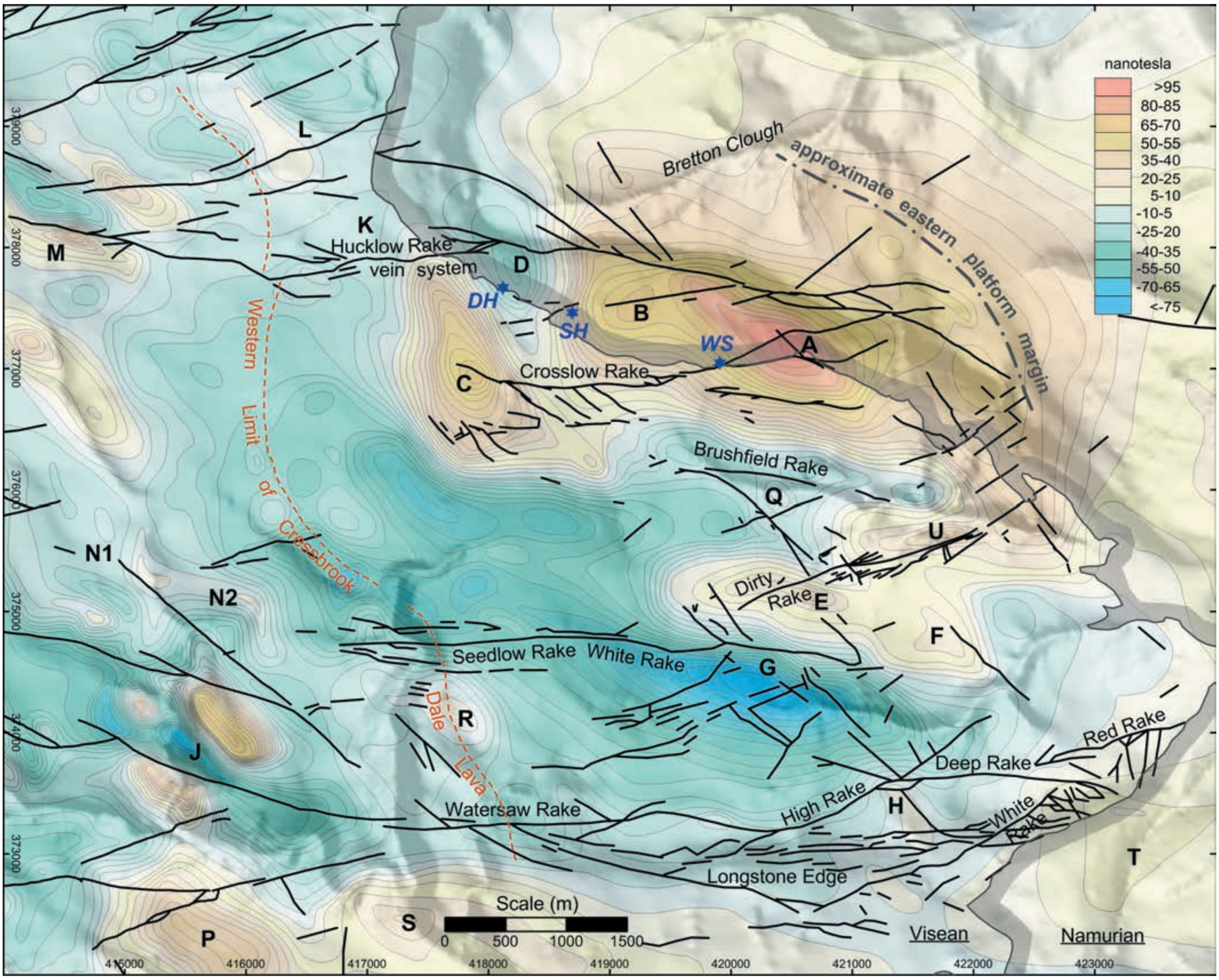


***Figure 13**. Total-field magnetic flux densities, with anomalies lettered as in text, and mineral veins superimposed; (after BGS HiRES survey). Blue stars are relevant stream sinks; DH, Duce Hole Swallet; SH, Swevic House Swallet; WS, Waterfall Swallet.*

margin trends northwest across the flank of the A-B magnetic anomaly, close to a group of three minor magnetic maxima. It appears that the Eyam volcano erupted very close to the eastern margin of the carbonate platform, and post-eruption carbonate sediments (the upper Monsal Dale Limestone) built up around it.

A magnetic negative (D) coincides with the depression in the upper surface of the Cressbrook Dale Lava discovered by underground drilling in Milldam Mine (Fig. 8). This suggests that the Stanley Moor anomaly (C) is likely to represent an individual volcanic mound in the lava field, and the contours of the A-B-C anomaly may provide a general image of the topography of this part of the concealed volcanic landscape. Apart from the Great Hucklow No. 7 borehole (Fig. 2, #12), there are no other borehole data to confirm its shape. The Great Hucklow borehole was terminated soon after it penetrated the lava, so did not reveal its thickness.

Additional evidence to support the suggestion that magnetic features B-C-D may approximate to the shape of the upper surface of the lava lies in the hydrogeology. Groundwater flow in the limestone is karstic, and open cavities were commonly encountered by the miners. Water sinking at Duce Hole Swallet (Fig. 13), flows underground northwards beneath the surface drainage divide, and across the Hucklow Rake mineral vein system, to rise 3 km away, after a fall of 105m, at Bagshawe Cavern, near Bradwell (Christopher et al., 1977). In contrast, water sinking at Waterfall Swallet probably flows south and then east before entering Carlswark Cavern, near Stoney Middleton, and draining to the Moorwood Sough (J. Beck, pers. comm.). Swevic House Swallet has been shown to drain both north and south (Gunn, 1998), so is very close to the groundwater divide. It appears that mounds and valleys in the impervious upper surface of the lava could locally influence the paths of groundwater flow.

The outcrop of the Litton Tuff along Litton Edge (Fig. 6) has no magnetic signal, indicating that it has a low magnetic susceptibility unlikely to affect any signal from the underlying lava. This may be caused by the presence of pyrite rather than iron oxide minerals.

The thick hyaloclastite beneath Longstone Edge, between Betney Cop and Bleaklow is associated with a weak anomaly (H), but this material also appears to have a low magnetic signal compared to that of the lava beneath the southern side of Eyam-Hucklow Edge (both lie beneath about 100m of sedimentary cover). This may be due to a melt temperature less than 500ºC or to rapid underwater quenching, either of which may have prevented ferromagnetic minerals from aligning with the Earth's magnetic field (M. Harwood, pers. comm.). Moderate positive anomalies (E and F) occur around High Fields, while a steep gradient exists between these feature and a deep magnetic low (G) along upper Coombs Dale. A shallower magnetic low (Q) separates the E-F and A-B-C magnetic highs. The E-F magnetic anomaly may lie over another volcanic mound, but there is insufficient borehole data to confirm this. The local thickening of the Litton Tuff, and the tuff in Goddard's Quarry, may be associated with a reactivation of an earlier volcanic mound in this area. The steep gradient between E and G may define a sharp boundary between the lava from the Eyam vent and the hyaloclastite erupted from Longstone Edge; alternatively, the deep low at G may be associated with a gap between the two flows where no volcanic material exists.

A prominent dipole anomaly (J) is associated with the outcrop of the Tideswell Sill, and a smaller dipole anomaly (M) lies over the faulted intersection between the Upper and Lower Miller's Dale Lavas and the Potluck Sill. These older lavas only appear to be associated with irregular, low-amplitude anomalies near their outcrops (N1 and N2), with no indication of any concealed thickening as they dip eastwards towards their terminations. The amplitude of the magnetic signal from the Potluck Sill (west of these maps) is low compared to anomaly A, and is difficult to reconcile with the 180 m of dolerite that is known to underlie it.

Magnetic anomalies P and S imply that another accumulation of concealed volcanic rocks underlies Brushfield Moor and Monsal Dale. Anomaly P is unlikely to be related to the Upper Miller's Dale Lava; this thins eastwards from its outcrop around Miller's Dale and Taddington and is represented by only 3m of tuffaceous mudstone at a depth of 73 m in a borehole just north of the Brushfield farms. The Lower Miller's Dale Lava is also unlikely to be very thick there, or it may be absent, as in Cressbrook Dale. These anomalies are more likely to relate to a deeper source (deeper than the 100m in the borehole), and may relate to the Lees Bottom Lava or the Shacklow Wood Lava. Magnetic anomaly R coincides with Wardlow Hay Cop, and currently has no explanation, other than potential volcanic material at depth. Anomaly T lies on Namurian outcrops, with no other information to identify its cause.

The featureless area at K (Fig. 13) encloses High Rake Mine and the 132m of concealed igneous rock encountered during shaft sinking. There is no recognisable magnetic anomaly to associate with either an intrusive sill or an accumulation of lava of that thickness. Equally, there is no distinctive linear magnetic anomaly to confirm the existence of a dyke, although this may be the consequence of its depth below the ground surface and its presumed narrow width. Even though the geophysical flight lines crossed the proposed dyke at an angle of 45º, the resolution of small-wavelength magnetic signals, such as might be expected from a narrow, deep source, is limited by the flight line ground clearance, which was 90m for this survey. A similar problem with non-detectable east-west dykes has been encountered in Scotland (Busby et al., 2009). The east-west alignment of dipole anomaly M suggests that it may be associated more with an intrusive dyke as it nears the ground surface rather than with the outcrops of the Miller's Dale Lavas.

Comparison of the magnetic and structural maps (Figs. 3, 8 and 13), shows that the Wardlow Mires structural basin (as defined by the upper surfaces of both the Cressbrook Dale Lava and the Litton Tuff), coincides with the area of low magnetic relief between the positive anomalies C, E and R. Located between possible volcanic mounds, this is an area where the lava is likely to be thinner. The synclinal structure could be re-interpreted as having been initiated by draping carbonate sediment over an uneven sea-floor topography on the submerged lava field, with subsequent infilling of the deeper areas. Gentle folding caused by Variscan deformation may have deepened a pre-existing sedimentary basin trapped between rigid volcanic mounds, rather than being solely responsible for its creation. Similarly, the anticlinal structure east of the Wardlow Mires basin coincides with the magnetic highs A, E and H. Rather than being a simple tectonic feature, perhaps this was also a group of draped volcanic mounds enhanced by later compressional folding?

The rapid west-to-east decrease in thickness of the limestone between the Cressbrook Dale Lava and the Litton Tuff (Fig. 9) is consistent with the shoaling of the sea floor against the probable volcanic mound suggested by magnetic anomaly C (Fig. 13). The proposed area of convergence of the Tuff with the Lava, where the limestone may have zero thickness, coincides with the A-B magnetic high associated with the Eyam Volcano.

Implications for mineralisation

Numerous fracture-controlled mineral veins transect the limestone plateau between Longstone Edge and Eyam-Hucklow Edge (Fig. 13). Most have a calcite-fluorite-barite mineral suite with minor galena (Rieuwerts, 2007; Ford & Rieuwerts, 2000). Vein widths are very variable, and fracturing of the limestone occurred in more than one phase (Quirk, 1993; Hunter, 2009). Many of the shorter veins belong to an apparently conjugate set with NE-SW and SE-NW orientations, while the longer veins have a general east-west orientation. The latter, particularly the High Rake and Hucklow Rake systems are large-scale mineralised structures that have been mined intermittently for at least four centuries. Production of fluorspar from High Rake only ceased in 2010, while Hucklow Rake, though not mined since 1999, is still considered to contain significant resources of the mineral.

Horizontal slickensides on faulted surfaces are commonly associated with the larger-scale east-west veins, and en-echelon, sinistral displacements of ~130m and 150m respectively can be estimated for the High and the Hucklow Rake vein systems. In contrast, many of the NE-SW and SE-NW veins, often called scrins, were narrower and less well mineralised. They are generally parallel to the major joint sets in the limestone and some scrins may be little more than enlarged joints filled with mineral. The short, east-west mineral veins located along the scarp slope of Longstone Edge have vertical slickensides, and are interpreted as early tensional fractures associated with flexing along the monoclinal axis (Hunter, 2009). These early fractures appear to have been intersected and laterally displaced by the later White Rake wrench fault.

Some of these mineral veins are aligned with magnetic anomalies related to the lava field concealed beneath (Fig. 13). A radiating pattern of mineral veins at Bleaklow is located at magnetic anomaly H, which lies above the thickest combined accumulation of igneous rock (Cressbrook Dale Lava and Litton Tuff together) along Longstone Edge. The radial pattern of veins may have originated as early fractures associated with settlement and flexing over the volcanic dome before a lateral stress field was imposed. East-west wrench faulting caused by the stress field appears to have exploited this previously weakened zone to create the important High Rake – Deep Rake mineral vein system. Repeated episodes of mining have probably obliterated all structural evidence of mineral phases in the main intersection zone. However, exposures of scrins visible today in the side-walls of the High Rake – Bow Rake open-pit mine suggest that they differ from the major east-west vein system, being narrower, barely mineralised and with no obvious indication of lateral displacement (Fig. 14). These characteristics are consistent with their formation as a separate and possibly earlier generation of fractures, although proof of this is lacking.

Other coincidental alignments between mineral veins and magnetic anomalies (Fig. 13) include: White Rake with the steep gradient between anomalies E and G; Dirty Rake, which connects anomalies E and U; Crosslow Rake, which connects anomalies A and C, including a bifurcation on either side of anomaly A; and the Hucklow Rake system, which is aligned with the northern side of anomalies A, B and C and then extends westwards to anomaly M, possibly following a deeper intrusive dyke. All of these named mineral veins belong to the larger, better-mineralised group that lie east-west and were the product of later-phase wrench faulting. Neither Watersaw Rake nor Seedlow Rake are associated with prominent magnetic features, although veins or unmineralised faults extend westwards from Watersaw Rake towards anomaly J (associated with the Tideswell Sill) and around the northern flank of anomalies P and S. The magnetically quiet area between Wardlow Mires and Tideslow (Fig. 2), which is underlain by thinning Cressbrook Dale Lava and a thickening Litton Tuff, is notable for the apparent absence of mineralised faults and fractures. The northern area of magnetic interference (Fig. 13, L) is most likely to be caused by the intersection of a series of ENE-WSW mineral veins with easterly-dipping lava beds. These veins shows sinistral faulted displacements, comparable to the main east-west veins, and also appear to converge westwards towards the area surrounding the Peak Forest Sill.

***Figure 14**. Wager's Vein (dark brown) cutting Monsal Dale Limestone in the High Rake open pit mine near on Longstone Edge in 2009; face height is 60m.*

The Eyam Volcano

Interpretation of the subsurface geology and airborne geophysics indicates that a lava field with a cluster of several individual volcanic mounds of variable relief exists concealed beneath the undulating limestone plateau between Longstone Edge and Eyam-Hucklow Edge. The largest of these mounds, containing massive and amygdaloidal basalt at least 72m thick, lies west of Eyam and is here named the *Eyam Volcano*. It could have formed an emergent island in the shallow Brigantian sea, surrounded by smaller volcanic cones on an irregular sea floor. It was subsequently buried during relative sea-level rise by onlapping layers of carbonate sediment that formed the remainder of the Monsal Dale Limestone. The extinct lava field, after becoming enveloped by the limestone mass, may have behaved as a rigid foundation rock that continued to influence the subsequent local geological evolution, beginning with reactivated eruptions of volcanic ash (part of the Litton Tuff) and differential settlement and compaction of the overlying limestone. During the period of Variscan deformation, the inherited structure of the lava field appears to have exerted some control upon the gentle folding of the limestone, as well as the locations and orientation of fracturing, major wrench-faulting and the hydrothermal mineral veins that have been extensively exploited.

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John Hunter
Quintessa Ltd, Birchwood Park, Warrington WA3 6AE
miner@aditlevel.co.uk

Richard Shaw
British Geological Survey, Keyworth NG12 5GG
rps@bgs.ac.uk

ID	name	source	ID	name	source
1	Wardlow Mires borehole No.1	1, p.91, 378	42	Sallet Hole Mine sough	11, p.123
2	Wardlow Mires borehole No.2	1, p.378	43	Hard Shaft	9, p.60
3	Littonfields borehole	1, p.69, 373	44	Slater's Engine borehole	11, p.124.
4	High Rake Mine shaft	2	45	Shuttle Rake Mine	9, p.53
5	High Rake underground raise	2	46	Crossdale shaft	9, p.60
6	Hill Top Mine shaft	3	47	Goddard's borehole 1	12
7	Mock Mine	3	48	Goddard's borehole 2	12
8	Nether Liberty Mine	3	49	Goddard's borehole 3	12
9	Smithy Coe Mine	3	50	Goddard's borehole 4	12
10	Old Edge Mine	3	51	Goddard's borehole 5	12
11	New Edge Mine	3	52	Goddard's borehole 6	12
12	Great Hucklow No.7 borehole	1, p.94, 102	53	Goddard's borehole 7	12
13	Hucklow Edge No.1 borehole	1, p.92, 367	54	Victory shaft	4
14	Hucklow Edge No.2 borehole	1, p.94, 371	55	Burnt Heath shaft	4
15	Dustypit Mine	1, p.94	56	Cliffstile Mine shaft	4
16	Middleton Dale (No.4) borehole	1, p.96, 375	57	Wren Park Mine	5
17	Milldam Mine shaft	1, p.94	58	Darlton borehole DH1	13
18	Broad Low (No.6) borehole	1, p.94	59	Darlton borehole DH2	13
19	Little Hucklow borehole	1, p.94	60	Darlton borehole DH3	13
20	Earnslow Mine shaft	4	61	Darlton borehole DH4	13
21	Watergrove sough intsecn.2	5, p.123	62	Darlton borehole DH5	13
22	Watergrove sough intsecn.1	1, p.94	63	Darlton borehole DH6	13
23	Watergrove forefield shaft	6, p.42	64	Limestone borehole 17NE14	14
24	Victory Level intsecn.	5	65	Limestone borehole 17SE12	14
25	Glebe Mine shaft	1, p.95	66	Limestone borehole 17NE12/13	14
26	Glebe Mine u/g borehole	16, p.86	67	Milldam bhole 35/89 (slit 5)	10
27	Ladywash Mine u/g borehole	1, p.95, 372	68	Milldam bhole 1/91 (slit 14 S side)	10
28	Ladywash Mine shaft	1, p.28	69	Milldam bhole 72/90 (slit 14 N side)	10
29	Eyam borehole	7, p.57	70	Milldam bhole 59/90 (turnaround)	10
30	Cressbrook Dale outcrop	Field visit	71	Milldam bhole 22/91 (C drive, N side)	10
31	Longstone Edge bhole SK17 SE/2	8, p.32	72	Milldam bhole 23/91 (C drive, S side)	10
32	Longstone Edge bhole SK27 SE/19	8, p.32	73	Middleton Engine Mine	10
33	Longstone Edge bhole SK27 SW/4	8, p.32	74	Tideslow New Engine shaft	15
34	Longstone Edge bhole SK27 SW/5	8, p.32	75	Robinson Old Grove	15
35	Longstone Edge bhole SK27 SW/8	8, p.32	76	Litton Tuff outcrop	Field visit
36	Longstone Edge bhole SK27 SW/1	8, p.32	77	Wardlow Sough raise	4
37	Longstone Edge bhole SK27 SW/20	8, p.32	78	Cackle Mackle Mines	4
38	Longstone Edge bhole SK27 SW/10	8, p.32	79	Seedlow Mine shaft	4
39	Longstone Edge bhole SK27 SW/15	8, p.32	80	Neptune Mine	Field visit & 4
40	Deep Rake (Backdale Mine)	9, p.61	81	Old Edge vein crosscut borehole	16, p.86
41	Castlegate Lane outcrop	Field visit			

source	reference
1	Stevenson & Gaunt, 1971
2	Bagshaw Collection, 1852
3	Lead in the veins, 2009
4	Beck, 1980 & pers. comm.
5	Rieuwerts, 2007
6	Ford, 2010
7	Gatliff, 1982
8	Aitkenhead et al., 1985
9	Carruthers & Strahan, 1923
10	Glebe Mines Ltd
11	Walters & Ineson, 1981
12	Cemex UK Ltd
13	Tarmac Central Ltd
14	Gatliff, 1982
15	Cook, 1780
16	Dunham, 1952

***Appendix Table*.**
Sources of numerical data used for the structural interpretations. Locations as on Figure 2.

Slope geomorphology and threshold slopes at Callow Bank, Hathersage, Derbyshire

Martin Cross

Abstract: Recognition of threshold and slope classes within a region indicates slope units where specific geomorphological processes are operating, and may be used to predict slope hazard areas. Using slope profile surveys and GIS techniques, analysis of slope form in the Callow Bank catchment near Hathersage identified characteristic and threshold slope angles. Geomorphological maps that adopt recognized characteristic and threshold slope classes allow an engineer or planner to identify slopes associated with particular hazardous processes.

Slopes exist in a variety of forms that reflect variations in climate, vegetation, rock type and rock structure. Characteristic angles and slope form are produced by specific geomorphological processes. All slopes are affected, though the rate at which they are being modified is usually extremely slow. Many slopes retain aspects of their form that were caused by processes no longer operating, notably in Britain from past glacial and periglacial activity. The main processes affecting slope form include mass movement, weathering and soil formation, and the movement of water and weathered slope material (regolith). The character of the materials can affect the processes involved.

Threshold slope angles

These may be regarded as the boundaries above, or below, which particular geomorphological processes cannot operate (Chandler, 1970; Carson and Petley, 1970; Anderson *et al*., 1980; Brooks *et al.* 1993; Montgomery, 2001). The various mass movement processes, including deep and shallow slides or flows, may set limits to the angle at which a particular slope type may be maintained. The upper parts of scree slopes are commonly restricted to angles no greater than 36–38º, terracettes rarely occur below 32–33º, and first-time soil slips are more common on slopes >20º (Carson & Kirkby, 1972). Slopes above 45° undergo rapid retreat, and slopes of around 33–35° develop from these at close to the limiting angle for dry scree. This marks the upper limit for valley-side slopes, since any steeper than this are mostly free faces. Slopes of 25–29° replace the steeper slopes by retreat where rapid basal erosion is absent. This angle corresponds to the stability angle (threshold) of the weathered regolith material (Carson & Petley, 1970). Slopes of 5–9° are associated with the limiting angle for relatively rapid solifluction (Young, 1972).

43° - 45°:	slopes on fractured and jointed rock.
33° - 38°:	drained talus slopes.
25° - 28°:	slopes on talluvium.
19° - 21°:	slopes on granular soil debris.
8° - 11°:	slopes on cohesive material.

***Table 1**. Threshold slope angles related to soil lithologies (after Carson & Kirkby, 1972).*

Certain threshold slopes are more common, and relate to soil lithologies (Table 1). In the southern Pennines, straight segments on slopes at about 25° are considered to represent the angle of long-term stability for regolith, excluding clays (Carson & Petley, 1970). Breakdown of slope mantle during weathering determines reductions in the angle of internal friction of the soil (Cross, 2010); these affect the shear strength and cause changes in the stable slope angle (Fig. 1).

In South Wales, slopes showing clear evidence of planar failures within superficial material typically have angles of about 18° (Conway *et al.* 1980). In the same area, a survey (Table 2) related threshold slope angles to regolith, bedrock and process (Rouse & Farhan, 1976). Conclusions from the Welsh studies included:

1: processes of rapid mass movement can be used to interpret most of the valley side slopes in Britain, where the slopes are largely a relict feature of a former periglacial environment;

2: rock type, geological structure and resultant lithology of the regolith influence slope development;

3: glacial erosion created free-faces that developed large scree slopes under periglacial conditions;

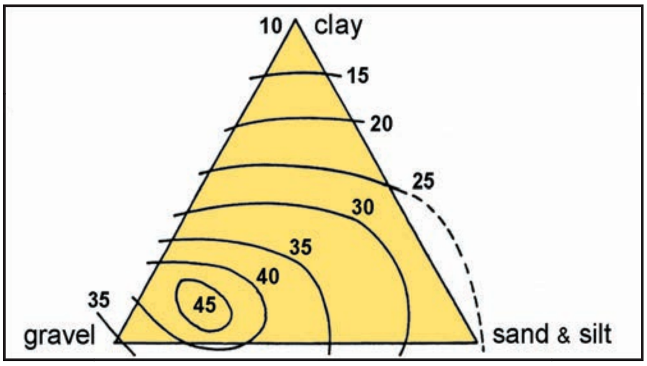

***Figure 1**. Angles of internal friction (in degrees) for different soil lithologies (after Kirkby, 1973).*

36°	Upper limit for valley side slopes
36° - 34°	Dry scree at the foot of free faces
30° - 28°	Fossil scree on sandstone
22° - 18°	Fossil scree on shale
10° - 8°	Solifluction slopes
6° - 2°	Flat areas of valley floors

***Table 2**. Characteristic threshold slopes angles (after Rouse & Farhan, 1976).*

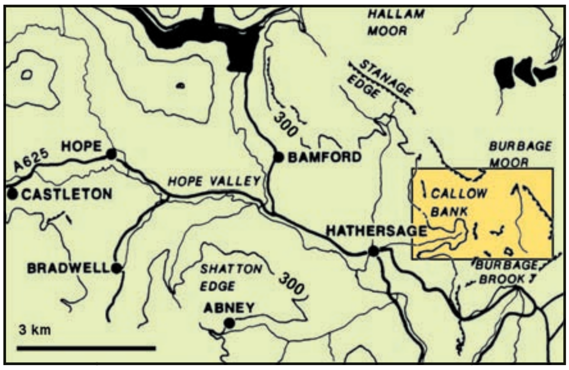

***Figure 2**. The Hathersage region, with the area on Figure 4 shaded brown.*

***Figure 3**. View up the length of the Callow Bank landslide, with the abandoned farm of Callow Bank on the right.*

4: weathering and down-washing of soil fines create an increase in fines downslope, so that the footslopes possess different groundwater regimes and slope angle thresholds differ from those of the drained upper scree slopes; and

5: rapid mass movements, particularly small-scale planar slides, continue to affect these slopes.

Callow Bank

The region east of Hathersage comprises high hill moors and plateau dissected by steep-sided valleys eroded through a succession of Carboniferous sandstones, mudstones and shales (Fig. 2). Locally the high plateaux reach altitudes of about 450m, and at their margins the well known gritstone edges formed by massive beds of sandstone overlook gentler valley sides. Callow Bank is the head scar of a landslide formed at the plateau edge in the lower leaf of the Chatsworth Grit, which is coarse grit and finer sandstone interbedded with about 20% of shale and mudstone (Fig. 3). Alternations of sandstones and sandy siltstones make up the lowest 18m of the lower leaf, and are exposed in the upper part of the slip face of the landslide. The thicker upper leaf of the Chatsworth Grit is the coarse-grained rock that forms Stanage Edge and the outliers of Higger Tor and Carl Wark to the south.

Solifluction deposits, 1.2 – 3.0m thick, overlie most of the shale and mudstone outcrops on the lower slopes below Callow Bank. The solifluction deposits are a matrix of sandy clay with lenses of rubbly sand, and containing cobbles, boulders and blocks of flaggy sandstone. Their material was derived from

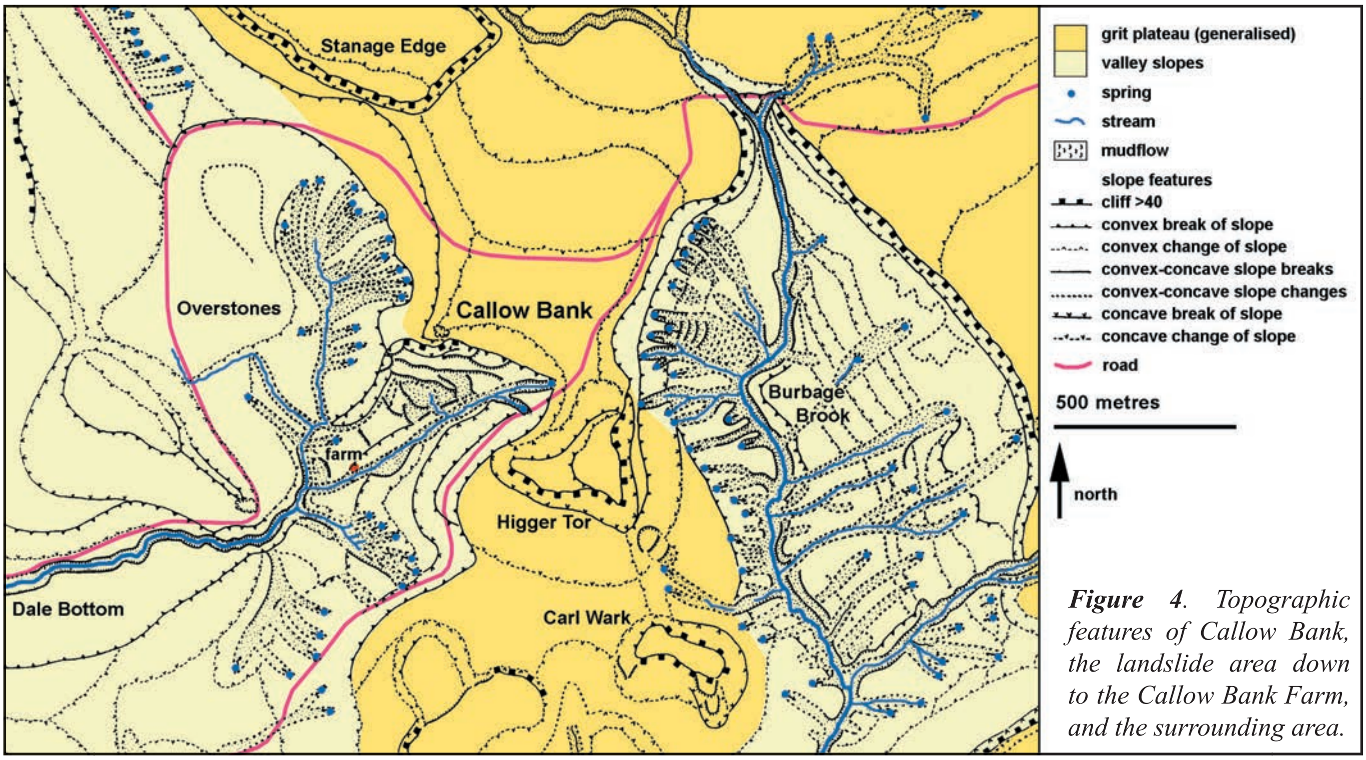

***Figure 4**. Topographic features of Callow Bank, the landslide area down to the Callow Bank Farm, and the surrounding area.*

the alternating sandstone and shale sequences by the action of periglacial freeze/thaw processes, and was then modified by solifluction flow and multiple sliding. They are notably heterogeneous, poorly sorted and broken by numerous discontinuous slip surfaces.

Heavy caprocks of sandstone resting upon less competent mudstone and shale have developed unstable slopes throughout the south Pennines (Johnson, 1980; Johnson & Walthall, 1979; Donnelly et al. 1998; Waltham & Dixon, 2000; Donnelly, 2008). The many forms of mass movement range from superficial solifluction lobes, terracettes and soil creep, through to deep-seated mudslides, debris slides and rockfalls.

Callow Bank is dominated by its multiple retrogressive landslide within a series of mudstones, siltstones, shales, sandy shales and thin sandstones (Fig. 4). The main landslide back scar is about 25m high, and rotational movements are deep-seated with moderate backward rotation of separate blocks (Fig. 5). The cause of failure was glacial erosion and valley over-steepening leaving the massive competent beds of sandstone exposed over weak shales. Rotational slides occur when maximum stress at the foot of the slope is transmitted by creep in the rocks within the slip zone (Petley and Allison, 1997; Rutter et al. 2003). The first slip movement probably developed from outward bulging and deformation at the slope foot, with retrogression taking place where tensional stresses caused movement outwards and downwards from the original slope (Petley, 2004). At least four major successive rotational movements have taken place. The deepest, and dominant, failure probably occurred on the black shale and seatearth that immediately overlie the Kinderscout Grit (which outcrops in the stream bed near the toe of the slide). Chemical and mechanical weathering of these shales may have induced deep-seated creep in the failure zone. At the foot of the landslide's back scar the main slide mass is characterised by topographic benches and depressions (Fig. 6). The lower section of the landslide, 300m below the back scar, has debris slide and mudslide components. This debris was more mobile, and moved by sliding outwards from the rotated units to create a low but uneven terrain as far as the tributary stream from Overstones, 500m from and 110m below the back scar (Fig. 4). Callow Bank Farm was built in 1720, and stands on the landslide debris slide. Ground movement, inevitable at its location, has distorted the buildings, which are now abandoned (Fig. 7).

***Figure 5**. Weathered shales in a rotated block within the upper landslde mass.*

***Figure 6**. Benches and depressions on the large landslide blocks directly beneath the back scar of Callow Bank.*

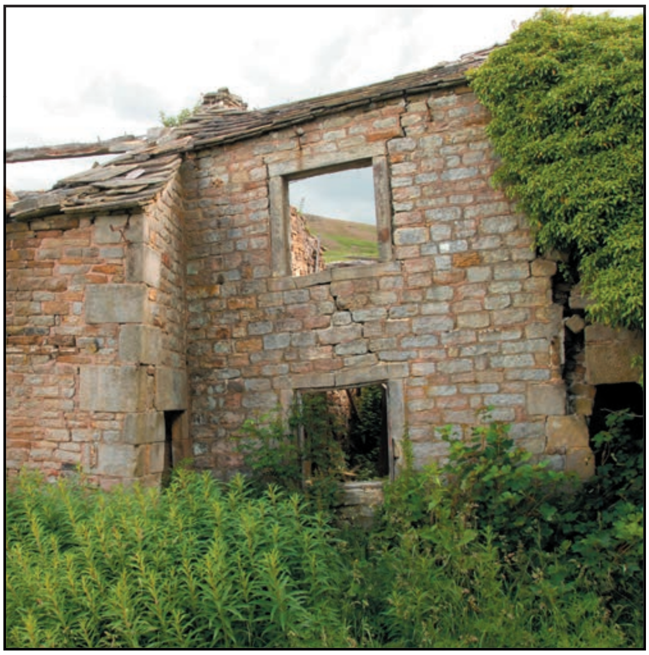

Figure *7. Distortion by ground movement of the old Callow Bank Farm, showing in the fracture through the stonework between the two window openings.*

The slope surveys

The slopes of Callow Bank were analysed by means of field profiling using a pantometer, and by desk techniques based on digitised contour maps. This research formed part of a more detailed study of landslide susceptibility mapping in the southern Pennines (Cross, 1998). Slope profiles were measured in the field with a pantometer 1.5m long (Pitty, 1968), and 3165 angles were measured to assess their frequency distribution. As part of a regional GIS project, 23,040 slope angles were collected over an area of 932 km^2 in the southern Pennines, which included the Callow Bank site (Cross, 1998). Digital versions of 1:10,000 topographic maps were layered with a grid at 125m line spacing, and slope angles of the central points within each grid square were calculated from contour interpolations (Carrara *et al.* 1991). Slope data from the GIS method are different to those from field measurement with the pantometer, so the two data sets are not directly comparable.

For the field measurements, the slope frequency distribution at Callow Bank peaks at 20º, which is within the threshold range for sandy soil regolith (19.6–21.5º). Small peaks in the histogram also occur at 24–25º and at 34º, which may be associated with the calculated threshold values of talluvium (25.6–27.5º) and scree (33.6–35.5º). The slope frequency distribution obtained from the slope profile survey at Callow Bank was compared to the slope frequency distribution derived from a regional GIS slope database which encompassed the Callow Bank study area.

In the GIS slope angle frequency distribution for the southern Pennines project, peaks occur at 21.8º and 26.5º (Cross, 1998). These also correspond closely with the threshold values for sandy regolith and talluvium. Another peak in this distribution occurs at 17.7º, which is similar to the predicted mean limiting angle for solifluction materials, and correlates with the slopes with identified shallow planar failures, both in South Wales (Rouse and Farhan, 1976).

The limiting angles 18.2º and 22.1º calculated for middle and upper slope sections respectively, coincide with the characteristic slope angle peak identified at 20.0–21.8º at Callow Bank and in the regional project. This represents the threshold angle for sandy soil regolith (19.6–21.5º), and appears to be related to the threshold angle for fossil scree slopes developed on mudstone and shale (18–22º). Slopes of 35.5º mark the upper limit for a valley-side slope, equal to that for dry scree), and slopes steeper than that are best described as free faces.

Engineering geomorphological mapping

Slope frequency studies reveal characteristic angles as limits for various processes of mass movement (Carson & Petley, 1970). In the southern Pennines, it has been possible to use engineering properties, process study and denudational history to interpret the genesis of present landforms, and this information can be conveniently shown on geomorphological maps (Al-Dabbagh & Cripps, 1987).

Many sites in the southern Pennines have infrastructure and buildings on slopes with evidence of former mass movement (Al-Dabbagh & Cripps, 1987). Risks of landslide re-activation may increase as a result of global climate change (Dehn and Buma, 1999; Collison *et al.*, 2000). With ground movements caused by extreme heavy rainfall events, and the greater pressure placed on development on steeper slopes, the identification of potential risk areas demands more attention by developers, planners and engineers (Doornkamp, 1994; Dietrich *et al.* 1993; Montgomery and Dietrich, 1994; Villa and McLeod, 2002). Probabilistic methods to identify potential

Figure 8*. Small back scars above and behind shallow planar failures within the regolith.*

2° - 6° Structurally controlled plateaux or valley floors
Upland plateaux with peat or regolith cover, localised creep mass movements and gulley erosion; lowland valley floors with alluvial floodplains or mudslide and earth flow debris from higher landslides.

12° - 14° Lower seepage slopes
Block debris from creep and solifluction, with gulleys from seepage lines; hill-wash and soil creep are active.

15° - 18° Convex creep slopes
Threshold angle for head and regolith with shallow planar movement on shallow or deep-seated translational slips.

19° - 23° Mid-level transportational slopes
Slope unit most affected by mass movements, forming the steeper valley side slopes, covered with landslide debris; threshold angle for fossil scree on mudstone and shale strata, and for sandy regolith.

24° - 28° Talluvial slopes
On talus at the threshold angle for talluvium; forming the steeper scarp slopes.

29° - 32° Fossil scree slopes
On fossil scree of sandstone, affected by deep-seated rotational slides and translational slides; slides may have lower debris flow components.

33° - 36° Dry scree slopes at the foot of free-faces
Drained scree at the foot of gritstone free-faces; at the threshold angle for dry scree.

37° - 45° Slopes on fractured or jointed rock
On fractured and drained rock; common below free-faces with rockfalls and toppling failures.

>45° Gritstone edges and free-faces
Gritstone edges and sandstone free-faces.

Table 3. *Geomorphological mapping units for the southern Pennines, based on surface morphologies, lithologies and threshold slope angles.*

landslide risk can fail where the historical record is not adequately reliable (Lee, 2009; Lee & Jones, 2004).

Experienced engineering geologists have traditionally used morphological mapping to isolate elements of slopes and define their characteristics (Cooke & Doornkamp, 1990; Fookes *et al*. 2003). Land elements of uniform gradient are identified in the field, their angles are measured, and the nature of the boundary between each element (concave or convex, break or inflection) is noted. It is important that the choice of these slope categories is carefully considered and reflects the characteristic and threshold angles of the mapped area.

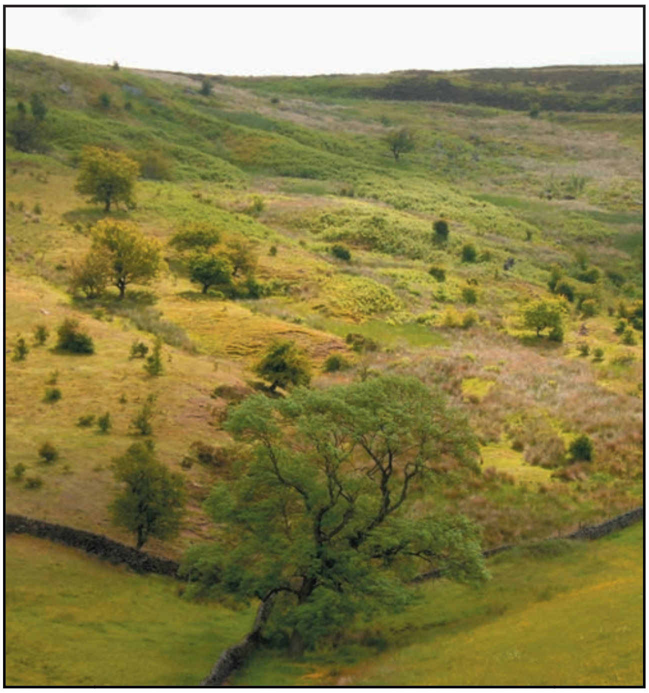

Figure 9. *The lower slopes of Higger Tor, with uneven ground on a regolith disturbed by solifluction movements and shallow mudflows.*

Geomorphological mapping units based on identified characteristic and threshold slope angles have been developed for the Callow Bank and southern Pennine areas (Table 3). These can help explain the genesis of slopes and the processes active on them, and are particularly relevant to detailed maps relating slope features to shallow mass movement and poor drainage. The units are generally comparable to those identified in Longdendale (Johnson, 1981). Large areas of the southern Pennines possess slopes that are unsuitable for building and engineering work unless ground investigation is thorough and remedial measures are designed and placed to maintain slope stability. Landslide movements are most likely to occur on slope units where weak shales form slopes over-steepened by erosion, where sandstone caprocks overlie less competent shales, and where springs have developed high pore-water pressures on the valley sides.

Deep-seated landslides appear to be located in two zones within the slopes of the southern Pennines (Johnson, 1980, 1981). One zone is at high elevation where slopes are generally concave; failures occur along bedding-plane slip surfaces with rotation in the upper parts of the slide. The second zone has deep-seated, rotational landslides on slopes at lower elevations where stream erosion at the toe of the slopes has undermined their stability.

Shallow failures tend to be more localised, and are particularly influenced by changes in the ground water regime (Fig. 9). Until drained, they may be highly susceptible to further movement if their temporary equilibrium is disturbed. The recognition of these areas is important to engineering projects on slopes. Many of the foot-slope units in the southern Pennines are covered with landslide and solifluction debris that may be up to 20m thick with numerous slip surfaces.

Much of the landscape of the south Pennines can be interpreted as a relic feature of glacial, periglacial and mass movement that is being superficially modified by current processes. Its detailed interpretation, through the application of geomorphological mapping, is important in identification of the areas of potential risk for planning and development.

Figure 10*. Broken and disturbed ground at the upper end of the Callow Bank landslide.*

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Martin Cross,
Scott Wilson Limited, Manchester.
martin.cross@scottwilson.com

Elias Hall, pioneer mineral surveyor and geologist in the Midlands and Lancashire

Hugh S. Torrens and Trevor D. Ford

Abstract: Elias Hall (1764-1853) was a pioneer Midlands and Lancashire geologist. Two significant influences allowed this man of humble origins to make original contributions to geology. The first was the arrival in Derbyshire in 1807 of John Farey, William Smith's most important pupil, who opened local eyes to the realities of Smith's stratigraphy. The second was the later establishment of the British Association for the Advancement of Science, with which Hall was involved from its beginning in 1831. But attitudes to the low historical importance of practical geology have since meant that Hall's work has been too long forgotten.

A gravestone, erected in 1861, in the southeast corner of Castleton churchyard bears homage to Elias Hall (Fig. 1). It was erected seven years after Hall's death, under the leadership of Edward William Binney (1812-1881), a Manchester solicitor and geologist who regarded Elias Hall as *the father of Lancashire geology* (Binney, 1862). Binney, who had arrived in Manchester in July 1835, had a social conscience, and took a great interest in the many working men's societies then active in Lancashire (Binney, 1912), to which he was first taken by Hall's fellow artisan fossil collecting friend and collaborator, the Chartist, Francis Looney. Binney felt that *both Hall and his labours had been forgotten in Castleton* (1862, p. 95). Hall's 1834 map included a small part of northwest Derbyshire, and followed the work of Whitehurst (1778, 1786), Farey (1811-1817) and Watson (1811).

Hall evidently had a devoted following, particularly in Lancashire, yet later he became little known among historians of geology. His map of the Lancashire coalfield was rather later than the county series compiled by William Smith (1769-1839), but never completed for financial reasons. Smith's county maps did not include Lancashire, but Hall adopted his methods, having been introduced to them by Smith's pupil Farey, and he produced models, then sections, and finally maps of the Lancashire coalfield and surrounding areas, of which only few copies survive. Hall's coalfield map was the first geological map of a large part of Lancashire.

Figure 2. *Elias Hall, in his later years.*

Elias Hall's family history

Elias was the third child of Abraham (1728-1803) and Martha Hall (1739-1769 - née Royse), daughter of Daniel and Hannah Royse, one of the many Royses involved in the lead mining industry around Castleton. Abraham was described as a yeoman, so he had a small estate and was middle class; his father was another Elias, born in Hope in 1691 and died in Castleton in 1749. Abraham and Mary were married there, by licence, on 4 September 1759. The International Genealogical Index wrongly renders her maiden name as Rose. Elias' elder sisters were Nancy (baptised 12/7/1760) and Hannah (6/1/1762), and his younger brothers were Joseph (23/9/1766) and Micah (15/1/1769). Elias Hall was born in Castleton on 6th January 1764; he was baptised the next day.

In Memory of Elias Hall, the geologist, who died on the 30th day of December 1853 aged 89 years. Born of parents in humble life and having a large family to provide for, yet he devoted himself to the study of geology for 70 years with powers of originality and industry rarely surpassed. To mark the last resting place of one who had worked so long and so hard for the public, a few of his friends and admirers living at a distance have placed this stone.

Figure 1. *The inscription on Elias Hall's gravestone.*

A different paternity, and thereby a false relationship between Elias Hall and other contemporary Derbyshire mineralogists, was wrongly recorded by Maxwell

Craven (1996). Those he named were John Mawe (1766-1829) and a (John) Tatlow Tissington (born 1757). This was in fact, John (Tissington) Tatlow (1757-1824), whose son Anthony Tissington Tatlow (1789-1828) married Mawe's daughter in 1815. All this also confused Cooper (2006), who rightly pointed out the historical problem of exactly which Hall had guided the French geologist Barthelemy Faujas de St Fond (1741-1819) around Castleton and Peak Cavern in 1784; St Fond consistently called him *J. Hall... who gains a subsistence by conducting strangers into the cave* (Geikie, 1907). Later writers (Binney, 1862; Andrews, 1880; Croston, 1889) repeatedly claimed this had been Elias, who would then have been aged only 20. This may be what is now called an urban myth, created by Binney years after Elias had died.

The problem is that many Hall families then lived in Castleton and elsewhere in Derbyshire. Possibly all might be distantly related: the parish registers list nearly 200 Halls buried in Castleton churchyard alone. A Joseph Hall of Castleton had supplied Blue John fluorspar to Richard Brown & Sons marble works in Derby from around 1769; clearly this was not Elias's son, who was born, and died in the same month, in 1789, so any connection with Elias is unknown. Joseph Hall and family ran both Peak Cavern and the Peveril Museum in Castleton (thought to be the last house on the right going up Peak Cavern walk), but it is not known if Elias was then involved. Among the other Hall families in Castleton was Robert Hall, who was also described as a mineral surveyor and *as the first practical geologist of the Peak* about 1770 (Adam 1843, p. 363). An Ellis Hall, mineral surveyor, was later listed in both Glover's and Pigot's Lancashire Directories of 1828-9, and this variant of the name is found in the Castleton parish records as a son of Thomas Hall and Ann, born there October 1764. Elias Hall was baptised earlier in that same year.

Elias Hall

An engraving of Elias Hall in old age (Fig. 2) is dated February 1866, and was produced four years after Hall's gravestone had been erected, as a result of Binney's re-evaluation of Hall's importance. It is now in the Tilley collection at Derby Local Studies Library.

Elias Hall, then of St Michael's Parish, Derby, married Martha Holmes at St Werburgh's Church in Derby, on 21st June 1787 (Derbyshire Record Office) although her background remains unknown. Elias and Martha had twelve children (Fig. 3). Epitaphs to Esther and her daughter Harriet were added to Elias's gravestone c.1883. Three of these children (including Joseph and both Abrahams) died in infancy. Elias last appeared in Derby Directories in 1787, and must have moved back to Castleton thereafter (Cooper, 2006).

Martha, 10/1/1788;	**Joseph, 6/12/1789;**	**John, 13/9/1791;**
Abraham, 20/8/1793;	**Abraham, 1/12/1794;**	**Ann, 19/10/1797;**
Mary, 21/4/1800;	**Elias, 22/5/1802;**	**Hannah, 31/8/1804;**
Esther, 2/9/1804;	**Harriet, 16/10/1806;**	**Catherine, 18/3/1805.**

***Figure 3**. The children of Elias and Martha Hall (after Robert Rainford, based on an 1826 sampler made by Elias' daughter Esther, now in the family in Canada).*

Elias Hall's marriage record noted he was then a "Petrifaction Worker" in Derby. Later he was variously recorded as fossilist, mineralist, mineral collector, geologist or mineral surveyor in Castleton. His home there was a cottage in Cross Street next to the Nags Head (Shawcross, 1903), later much altered and now the Greystones shop.

Nothing is known of Elias Hall's education, though he is referred to in obituaries as self-educated. His schooling appears to have been above the standard for the time, but his spelling was highly idiosyncratic. The first indication of any interest in what was later called geology may be when Elias Hall's name is found written against the 3 February 1800 diary entry of White Watson (1760-1835) of Bakewell (Meeke, 1996). That they were already in contact is demonstrated by Watson's cash book (Meeke, 1997) which recorded dealings with "Elias Hall, Castleton stone dealer" from 29 July 1796. Watson was a petrifactionist and marble worker, who took a great interest in geology (Torrens, 2002).

From August 1807, the London polymath John Farey (1766-1826), who had become William Smith's most significant pupil from 1802, had been commissioned to undertake two projects in Derbyshire. The first, from late summer 1807, was for Sir John Sinclair (1754-1835), President of the Board of Agriculture, who commissioned Farey to undertake an extensive survey of the agriculture and minerals of Derbyshire (Farey, 1811-1817). The other was a private commission from the President of the Royal Society, Sir Joseph Banks (1743-1820), who owned an extensive estate at Overton, near Ashover, whose minerals he wanted surveyed by Farey; the map and report were not published (Torrens, 2002). Farey's work changed the views of both Watson and Hall as to the significance, and economic potential, of the serious study of stratigraphy in Derbyshire.

From 1808, Hall helped John Farey by showing him round the Castleton area while Farey was compiling his three volume work on the Minerals and Agriculture of Derbyshire for the Board of Agriculture (Farey, 1811-1817). The first printed notice of Hall's geological work appeared in July 1809 in Tilloch's Philosophical Magazine, volume 34, no. 135. This was clearly inserted at John Farey's suggestion, who was then a prolific contributor to that journal. It reads: *Elias Hall, opposite the Inn, at Castleton, Derbyshire, Manufacturer of Ornaments of every description, in Fluors and other Spars, (usually called Petrifactions,) in Gypsum, Marble, etc, takes this opportunity of informing his Friends and the Public, particularly such as are travelling the High Peak of Derbyshire, with a view to the Geological and Scientific Information which that interesting and astonishing District is calculated to afford, that he has a large Collection of Specimens* *of Native Fossils* [minerals], *Minerals and Toadstone Strata constantly on Sale; as well of the Rocks, Spars, and Metallic Ores, as of the interesting organic Remains* [fossils] *of the Animal Kingdom peculiar to these Strata: which Specimens being collected by himself, he will be able to point out to Collectors, the local and relative Situation of each in the Stratification of the District.*

"Opposite the Inn" may refer to the Castle Hotel, and the opposing property later became Needham's Museum and spar shop. Hall's family connection with the Inn here is confirmed by Farey (1813) who listed his relative *Isaac Hall of the Inn, Castleton* as another who had given him information. This notice shows that Hall still continued here as a maker of Derbyshire Ornaments. The notice then continues: *By a reference to a model of the County of Derby, which Elias Hall has executed, by Permission, agreeably to the Mineralogical Map which Mr John Farey of London is executing of the whole County of Derby, he hopes to be able to explain fully to the Scientific Gentlemen or Ladies, who may do him the Honour to inspect his Factory and Collections, or take him out with them, in addition to the ordinary Guides, in their Excursions in the Neighbourhood, the Nature and Relations of every Particular worthy of Observation, respecting the Rocks, Caverns, Mines, Stratification, Dislocation of the Strata and extraneous Fossils of the District, according to the most recent Discoveries on the Subject; which, from their Importance and Novelty, cannot fail of giving much Satisfaction to the Curious. N.B. Orders for Ornaments punctually executed, Wholesale or Retail, and Ornaments restored, cleaned etc.*

The close connection between John Farey and Elias Hall is again revealed in Hall's first manuscript letter known to have survived. This letter (in the Bagshaw Collection at Sheffield Public Library, ref. Bag. C 587 69) is dated Castleton, 16 September 1810. In it Hall asked a Mr Birds for help with a series of mainly mineralogical questions which Farey had recently asked. Hall's letter ends *these are all or part requested by Mr John Farey, the remainder of his requests are in my Neighbourhood*. Mr Bird or Birds was another of Farey's contacts in Derbyshire, whom he recorded (1811) as *Thomas Bird, Mine owner and lead smelter of Eyam, near Stoney Middleton, Mineral Collector*.

This was the antiquarian Thomas Birds Esq. (1752?-1829), who had been a great collector of books, prints, paintings and china. These were auctioned after his death when his *Cabinets of valuable and rare Fossils* were to be sold separately. It was noted how his *well known and truly valuable Collection of FOSSILS is on sale by Private Contract, and consists of from fifteen thousand to twenty thousand specimens, chiefly English, has been one hundred years in collecting, and contains some of the finest and rarest specimens in the kingdom* (Liverpool Mercury, 24 July 1829). The word *Fossils* is here clearly still being used in its old sense; i.e. anything dug up, both minerals and fossils. Sadly the fate of this obviously extraordinary collection is unknown. It is possible that it passed into the collection of his collateral descendant James Adey Birds (1831-1894) who later died in Bournemouth (Anon., 1895). This collection was bequeathed to Derby Museum, where it is little recognised (Stanley, 1976).

Elias Hall's Models

Several of Hall's later publications carry notes or advertisements of models he had made to illustrate geology. The first notice of this had appeared in 1809. Farey (1813) wrote: *Elias Hall, Fossilist and Petrifaction-worker of Castleton, who, after revising my Mineral Observations with great labour, on all the great Limestone Tract north of Winster, and in some of the adjoining Shale and Grit Tracts, has completed several exact Models of this District, which exhibit the face of the Country, the Stratification, Mineral Veins, Faults etc in a very natural and perfect manner; some of which Models, in return for the kind services of this ingenious and deserving Individual, I have undertaken to show at my [London] House; or they may be seen at Castleton, together with a series of the several Minerals of this curious District. Adequate encouragement to Mr. Hall, in the disposal of these Models and his Fossils might perhaps induce him to examine the southern half of the Limestone District, with equal industry and care, and to include the same in one or in a separate Model.*

A reprint of the original flyer Farey produced to advertise Hall's models, which gave full details, appeared in March 1813 in Nicholson's Journal (Anon., 1813a). This recorded that Hall's first model, carved from wood, had been made under the patronage of both the Duke of Devonshire and Sir Joseph Banks. It noted how Hall had followed the same colouring Farey was using in his Surveys and listed those of the 11 lowest strata of the rocks depicted, of which samples were arranged on the east side of the model. This notice ended that Hall had made his own examination of this area, and had then compared it with Farey's report and manuscript maps. It ended that Hall sold labelled collections of the mineral productions of the Peak Hundreds, and that Farey from *a desire to promote mineral science and to serve Mr. Hall* kept some of Hall's models at his London home for inspection and sale at eight guineas each. Summaries were also inserted by Farey in other journals (Anon., 1813b, 1813c), and confirmed that Elias Hall had: *carved out a Model of [Derbyshire's] curious and rugged surface. The superficial scale is one inch and a quarter to the mile.*

These notices immediately attracted the former President of the Geological Society of London, George Greenough (1778-1855). Farey sent him his flyers on 9 March 1813: *If you will take such methods of distributing the Bills of Mr Hall's Models sent herewith, at the Geological Society or otherwise, as are most likely to serve Mr. Hall, it will greatly oblige me* (Greenough Archive, University College London). Farey soon noted, as his annotation to Greenough's copy of Joseph Townsend's book "The Character of Moses", how: *Mr Elias Hall discovered in the beginning of 1813 that the great fault bears ye course here mentioned at Lindale and near ----- and wet rake veins, as shown in his models, and that it is an inferior fault that proceeds through Bradwell and Great Hucklow and which turns along Hucklow Vein East and thence to Eyam and Stoney Middleton*.

Hall was soon also in contact with Banks, to whom he reported how he had, in the spring of 1814, extended his survey northwards, with a new *Model of the Strata of the Grand Ridge and the adjacent county east and west of it, almost as far as Westmorland* (Farey, 1814).

But Greenough was soon involved in a vicious dispute over whether or not his Geological Society should publish some of Farey's extraordinarily detailed geological work in Derbyshire. It did not, and so remains largely lost. So, in June 1816, Farey could now write: *I am sorry to add, that the very meritorious exertions of my friend Mr. Elias Hall have met just a similar fate* [as I]*, through the same Party; - no sooner was one of his Models shown, before several of its Leaders, than without waiting to examine a single particular of its laborious details, advantage was taken, of an injudicious use of rather too glaring colours, in Mr. Hall's first attempt, to raise a laugh, by the far-fetched and contemptible joke, that "a tray of Guts and Garbage in a Fishmonger's or Poulterer's Shop", rather than any thing else was called to the mind, by viewing this elaborate Model of the Stratified Hills and Dales, of a tract of Country! Such was the conduct of the Heads of a Geognostic Society* [i.e. the Geological Society of London, which Farey was later to name The Anti-Smithian Association]*, and such the reward of meritorious labours, out of its pale; and my Friend remains, and is likely to do, a considerable loser by what he has done* (Farey, 1817, v. 3, p. viii).

Joseph Banks was much more sympathetic towards such detailed stratigraphic work, because of the financial advantages it gave local land owners like himself. This connection also explains why the British Museum's curator of minerals, Charles Koenig (1774-1851), when he took a month's vacation in Derbyshire, in 1819, visited Hall in Castleton. There he ordered *two of Hall's models of the topography of Derbyshire and Cumberland (probably for his planned exhibit of British minerals arranged by counties)* (Smith, 1969, p. 255). Koenig's diary confirms that *on 24 September 1819 he paid into Farey's hand £11.3.0 for Elias Hall* for these. Sadly they too seem not to have survived.

Another geologist who was intrigued by Hall's models was the former Lunar Society member Jonathan Stokes (1754-1831) of Chesterfield (Torrens, 2010). On 20 March 1821 he wrote to Nathaniel John Winch (1768-1838) how a friend had *sent me a coloured geological map of the Lakes constructed from a model made by Mr Hall of Castleton, who I learn from Nicholson's Journal has extended his model of Derbyshire to the Lakes* (Linnean Society, Winch Archive 4:112). This must be from a later model that had extended Hall's work north to the Lakes. Hall's 1824 published section has a note in the margin which confirms that he had *constructed and Sells at Castleton, Models of the Strata of the High Peak, and others of the Mountains, Northward to the Lake District of Cumberland*.

The obituary notice by Binney recorded that *Elias Hall, fossilist and petrifactioneer, has completed several exact models of this [Peak] district which exhibit the face of the country, the stratification, mineral veins, faults etc*. Binney also noted *a model of the neighbourhood of Manchester, then housed in the Museum of the Natural History Society in Peter St.*, Manchester (Binney, 1862, p. 93-94). A model of the Lake District was also mentioned.

Models were also mentioned in the later appreciations of Hall's life's work by Croston (1868), Cash (1873), Wood (1987) and Cooper (2006). Appeals for information on Hall's models have failed to uncover any survivals (Torrens & Ford, 1977). A comparable model, attributed to F.A. Carrington 1848, was said to be in the Manchester Museum (the late Michael Eagar, pers. comm. 1977), but he then wondered if it had been confused with one of Elias Hall's. Again it could not be found after a recent enquiry. So, regrettably none of Hall's models have been located, though it is still possible that some languish in museum storerooms unsigned or unrecognized.

Without being able to examine Hall's models one can only speculate on what they might have shown. A reasonable guess is that they were block models with the strata painted on as with his later sections and maps. The first were certainly carved from wood, while later ones might have been cast in plaster. The latter would be more likely if multiple examples were to be available for sale: wooden models would have had to have been individually carved and painted. A boxed set of 26 wooden models of Farey's fault types (out of 56 illustrated by Farey in 1811) survives in the Geological Society's Library (Dearman & Turner, 1983) but it is not known either who made them, or when. They are made from various coloured wood sheets glued together. The Geological Society acknowledged Greenough's presidential donation of this *series of Farey's models* in 1841, but as Farey had died fifteen years earlier, it is possible these had been made earlier by Hall.

Elias Hall's Sections

Hall published several long geological sections, copies of which have survived. The earliest was *A Vertical Section of the Strata, published as the Act directs January 1 1824 by Wm. Phillips, Lombard St., London*. Phillips had previously been the Geological Society's Quaker printer and publisher, despite making a considerable loss. In 1824 he published an appeal for more philanthropy (Torrens, 2009) and this suggests

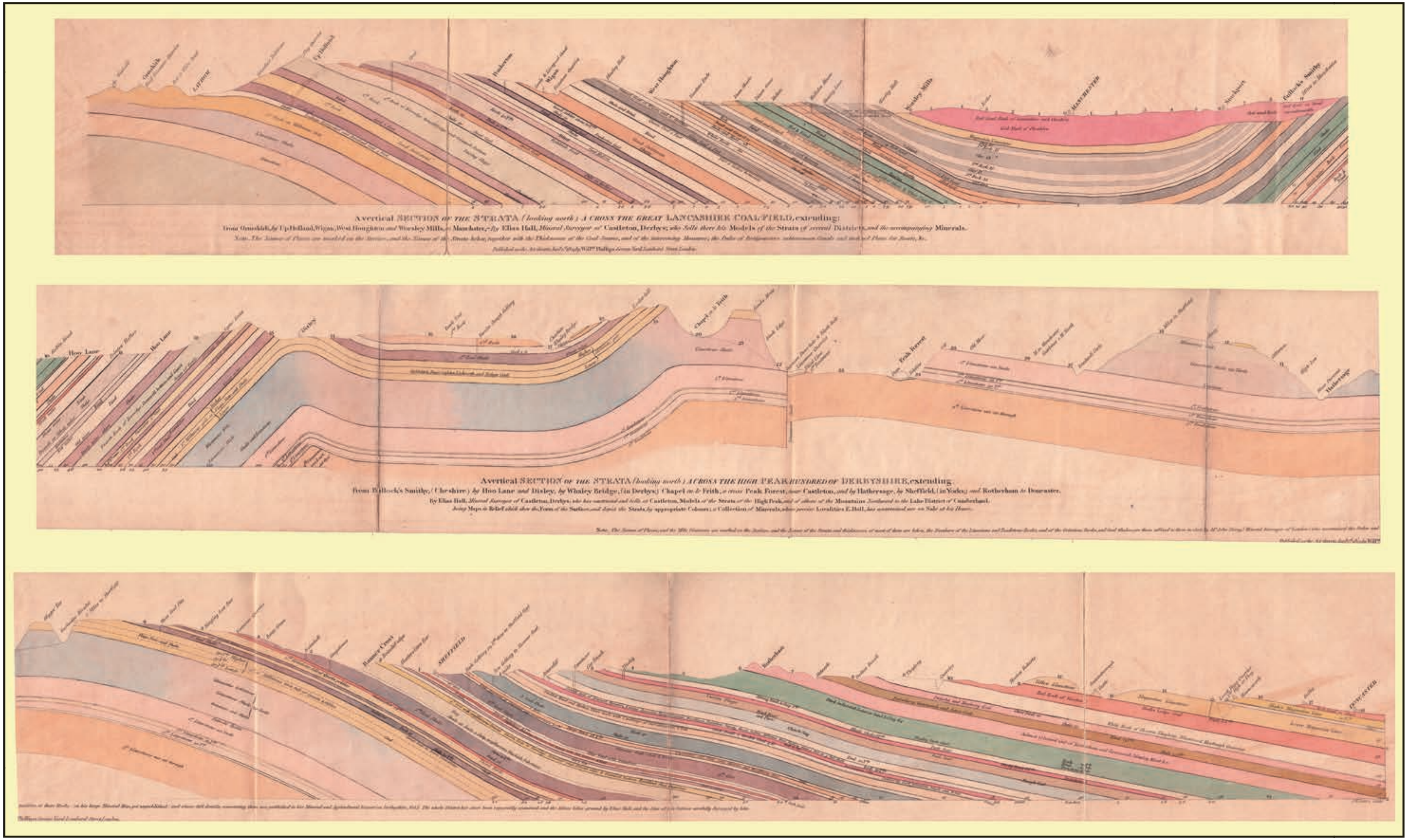


Figure 4. Elias Hall's geological section across the Pennines, in its first state (edition).

a likely reason why he then published Hall's section. It was by Elias Hall, now calling himself a mineral surveyor, following Farey's lead (Torrens, 2001).

The first notice of this section, in the Monthly Magazine of 1 July 1823 (p. 551), read: *Elias Hall, of Castleton, who in 1813 distinguished himself by preparing numerous stratigraphical models or maps in relief ... has since modelled the contour and strata of the grand ridge of hills, extending from Derbyshire to the lake hills of Cumberland. [He] has now in the hands of Mr. Lowry, the engraver, two vertical Sections of the Strata. The thicknesses of the several coal-seams and thicknesses of measures (of rock, shale etc) between them will be set down*. This shows that Hall's 1824 section was almost the last work produced by the most famous scientific engraver of his day, Whitehaven-born Wilson Lowry (1760-1824). He had long been interested in geology and been elected an early member of the Geological Society of London in 1808 and to the Royal Society in 1812. He was a close friend of both William Smith and John Farey, the last of whom must have organised this collaboration. Its publication was noticed after Lowry had died (Anon., 1824).

The section (Fig. 4) has two captions. The first shows the strata *across the Great Lancashire Coalfield* from Ormskirk through Manchester. The second shows those across *the High Peak of Derbyshire* from Bullock's Smithy through Chapel-en-le-Frith, Hathersage and Sheffield to Doncaster. It records that: *The names of the Strata and thicknesses of most of them are below. The numbers of the* [succession of four] *Limestone and* [three] *Toadstone Rocks, and of the Gritstone Rocks, and Coal Shales, are those affixed to them in 1808 by Mr. John Farey... who ascertained the Order and Position of these Rocks, on his large Mineral Map, yet unpublished. The whole District has since been repeatedly examined and the Mines below ground, by Elias Hall, and the Line of this Section carefully surveyed by him*. It clearly shows that Hall understood the stratigraphy and structure of the South Pennines and adjacent coalfields. The Duke of Bridgwater's underground canal to his coal mines at Worsley was shown. Manchester is in a syncline of Red Marls and Sandstone. A single fault (vertical) is shown at the contact of Limestone and Limestone Shale (Edale Shales) at Barmoor Clough and Doveholes, north of Buxton, where the contact is now regarded as an unconformity.

The section is known in two forms: one is a folded linen-backed strip 2 metres long by 13 cm high, made up of the segments glued together, in an original slip case with a printed red paper label; the other is an uncoloured sheet, 80 by 63 cm, with the three sectors of the strip one above the other. A partly comparable section was included along the southern margin of Hall's 1834 map of the Lancashire Coalfield. Chris Toland of Cheltenham has two versions; one is as above, but a later one has both brighter colours and additional engraved details.

A second group of sections (Fig. 5) is on a sheet entitled *A Geological Section exhibiting the Strata across the Coalfield of Lancashire, extending from Manchester ... to Clithero* by *Elias Hall, Mineral Surveyor. Castleton, Derbyshire and No. 20 Ridgefield, Manchester*. Dated 1831, this sheet measures 58 by 45 cm and was printed with colours and a scatter of figures added by hand. The sheet has three partly parallel sections with considerable detail of the sequence of coal-bearing strata with thicknesses in the collieries and their depths superimposed. The top section has Gypsiferous Marls capping the succession at Manchester. The middle section shows undulating Coal Measures and a single fault close to Oldham, labelled Red Tom Nook. The third section from near Rawtenstall to Clitheroe shows a synclinal arrangement with the Calder River and Padiham in the core. Some detail of the Millstone Grit sequence is shown, with Pendle Shale (broadly equivalent to the Bowland and Edale Shales) at the base, and the Carboniferous Limestone of Skipton and Clitheroe at the extreme right with Clitheroe Castle on the top. Curiously, a small sketch of Peveril Castle and Peak Cavern at Castleton has been drawn within the Carboniferous Limestone below Clitheroe Castle.

A later section, from after 1834 and still unlocated, was compiled *from the Irish Sea to the German Ocean* [North Sea] (Binney, 1862; Anon., 1900). This could have been an extended version of that from Ormskirk to Doncaster. Finally an undated, hand-coloured *Section of the Strata of the Earth extending from Conisbro, Rotherham, Sheffield in Yorkshire, Hathersage, Castleton, Peak forest, Buxton in Derbyshire to Macclesfield in Cheshire by Elias Hall of Castleton* survives in the William Smith collection at Oxford. An annotation by Smith concerns his Pontefract Rock, which was later called the Magnesian Limestone, and which he had first shown on his wonderful County Map of Yorkshire of 1821 (Phillips, 1844), which may help date this section.

Elias Hall's 1834 Lancashire Map

At some stage between 1824 and 1831, Elias Hall became involved in the coal-mining industry in Lancashire, and maintained an office in Manchester (at 20 Ridgefield in 1831; 53 Back King St. in 1834).

The best known of Hall's maps is his 1834 map of the Lancashire coalfield (Fig. 6). It is undated but is dedicated to Adam Sedgwick when he was Vice President of the Geological Society of London. The British Library dates it 1830; Whitaker & Tiddeman (1875) say 1831; while the Natural History Museum Catalogue and the Museum of Practical Geology Library Catalogue both give 1832. But copies of the Prospectus dated September 1833 survive in the Durham Record Office and at the Linnean Society, London (Fig. 7).

A letter to Greenough dated 11 January 1834 survives in the Greenough archive (University College London) from Richard Potter (1799-1886). It notes:

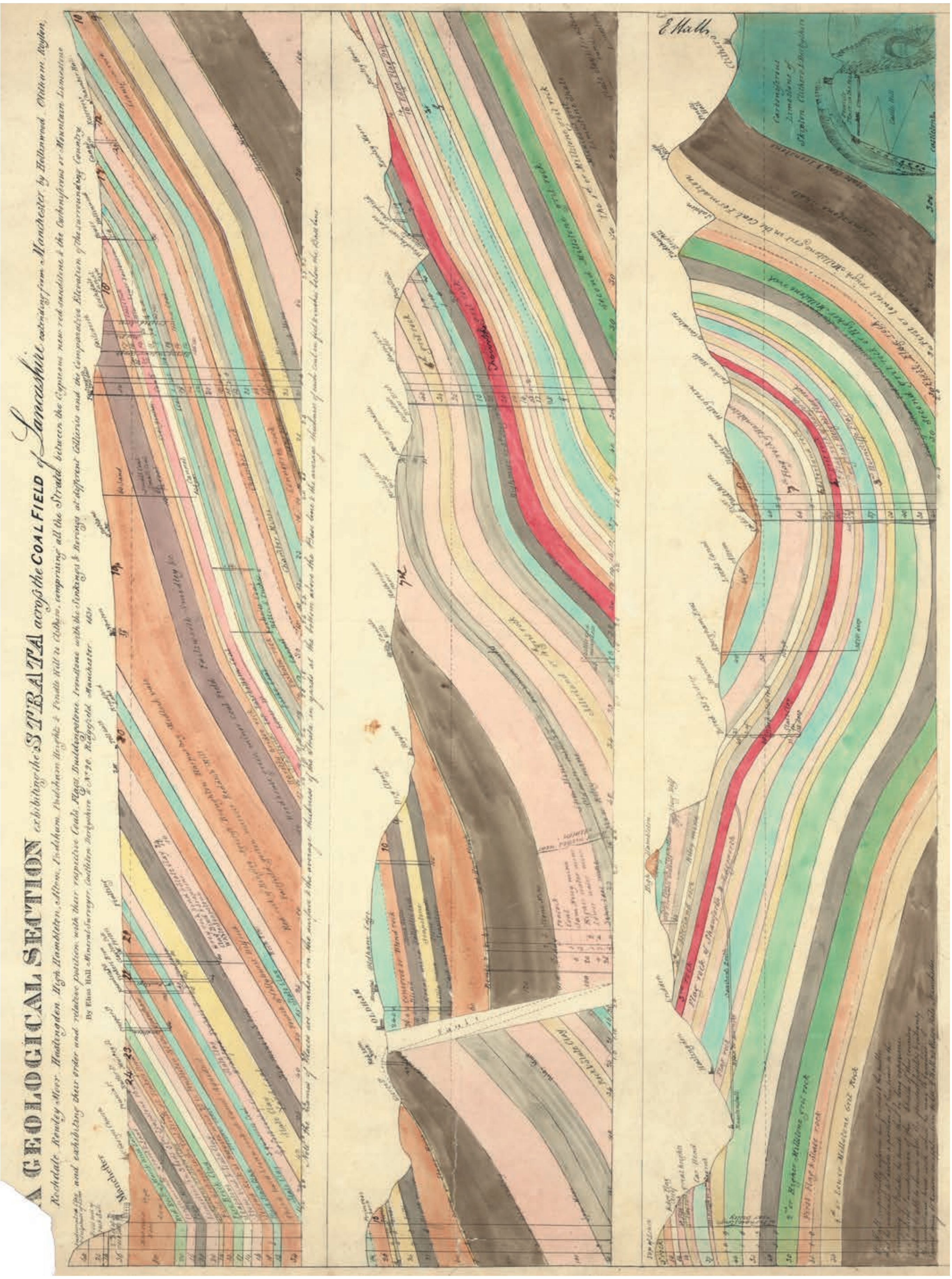
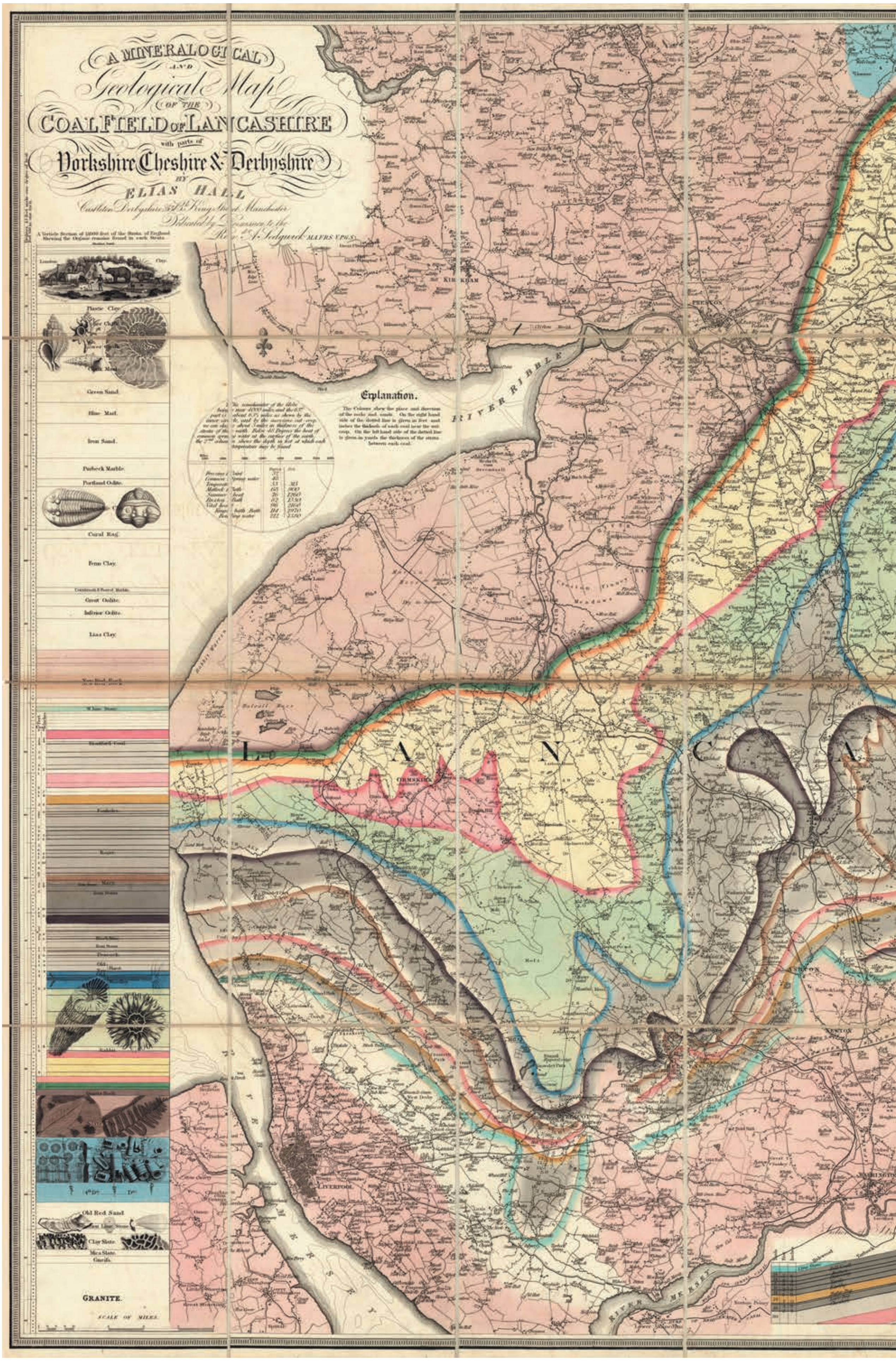


Figure 5. *Elias Hall's geological sections through the Lancashire coalfield.*

***(next pages)** **Figure 6**. Elias Hall's 1834 geological map of Lancashire.*


A MINERALOGICAL
AND
Geological Map
OF THE
COAL FIELD OF LANCASHIRE
with parts of
Yorkshire Cheshire & Derbyshire
BY
ELIAS HALL
Castleton Derbyshire & 31 King Street Manchester
Dedicated by Permission to the
Rev. A. Sedgwick M.A.F.R.S. V.P.G.S.
A Vertical Section of 12000 feet of the Strata of England Shewing the Organic remains found in each Strata
London Clay
Plastic Clay
Green Sand
Blue Marl
Iron Sand
Purbeck Marble
Portland Oolite
Coral Rag
Fens Clay
Great Oolite
Inferior Oolite
Lias Clay
Old Red Sand
Clay Slate
Mica Slate
Gneiss
GRANITE
SCALE OF MILES
Explanation.
RIVER RIBBLE
KIRKHAM
PRESTON
ORMSKIRK
LIVERPOOL
L A N C A
RIVER MERSEY


CLITHEROE
BURNLEY
BLACKBURN
HASLINGDEN
ROCHDALE
BOLTON
BURY
MIDDLETON
OLDHAM
LEIGH
STOCKPORT
ALTRINCHAM
Y O R K S H I R E
S H I R E
C H E S
D E R B Y S H I R E
...ta from Tarbock to Lathom the Coal in Feet & Inches below the base line the other Strata in Yards above the base line
Whiston
Railroad
Hill
PRESCOT
Stand
Rainford
Bickerstaff
Lathom Hall
Leeds Canal
Quartz Rock
Millstone Grit
Slate Clay
Limestone

Adam Sedgwick (1785-1873), Cambridge professor of geology.
William Buckland (1784-1856), Oxford professor of geology.
George Greenough (1778-1855), Geological Society founder.
Philip Egerton (1806-1881), fossil collector, landed gentleman.
John Dalton (1766-1844), Manchester chemist.
William Henry (1774-1836), Manchester chemist.
William Smith (1769-1939), stratigrapher.
G W Wood (1781-1843), merchant, MP for South Lancashire.
Mark Phillips (1800-1873), merchant, MP for Manchester.
Thomas Gisborne (1794-1852), MP for North Derbyshire.
Christopher Rawson (1777-1849), landed gentleman,
president of the Halifax Literary and Philosophical Society.
Edward Holme (1770-1847), Manchester physician/scientist.
John Phillips (1800-1874), geologist and Smith's nephew.

***Figure** 7. A list (perhaps incomplete) of subscribers to the 1833 Prospectus.*

the Bearer Mr Hall is now about setting off to London to get printed and coloured his geological map of the coal-field of South Lancashire and I avail myself of the kind permission you gave me when we met last in Cambridge [at the BAAS meeting in June 1833] to introduce him to you. So it is clear that Hall's map was published after January 1834.

The map was referred to as "yet unpublished" on the lower margin of Hall's 1824 section. There are at least three different editions (known as *states*) of the map. Greenough (1835) announced the publication of this first state at the Geological Society AGM on 20 February 1835, as of: *a county hitherto comparatively neglected. Mr. Hall is entitled to great praise for his intrepidity and perseverance; had he not possessed these qualities in an eminent degree, he never would have entered, as it were alone and single-handed, on so irksome and laborious an investigation. That the work is in many respects imperfect must be admitted, but considering the apparent disproportion of his means to his end, it is surprising that the author should have achieved so much: what he has left incomplete or inaccurate will be readily supplied*.

The engraver was George Bradshaw, St Mary's Gate, Manchester, but who the printer was and how many copies were printed are unknown, and only a few are known to exist in libraries and other collections. The map was on a scale of 1 inch to 1 mile and measures 120 by 90 cm. It was printed in black ink and hand-coloured in the style of William Smith's 1815 map of England and Wales, with dense colours marking the lower outcrops (bassets) of the coal seams and other units, and with the colour then fading down dip.

A verticle (sic) column of 15,000 feet of the strata then known (with names taken largely from Smith and Farey) is on the left-hand margin with units ranging from the Bagshot Sand [Eocene] down to the Old Red Sandstone [Devonian] and Transition Limestone [Silurian], with Mica Slate, Gneiss and Granite beneath. The sequence of coals is fairly accurate, but there are minimal details of the Millstone Grit and Carboniferous Limestone. Some sketches of typical fossils were superimposed in the column. The London Clay has a sketch of an elephant, horse, rhinoceros, giraffe and two humans, which are now assigned to the then unrecognised Quaternary. In the first edition, some fossils were engraved in wrong places. The first has a misplaced engraving of the Silurian *Calymene* trilobite in the Kimmeridge Clay. The second edition corrected this, added Highgate Sands to the Bagshot Beds unit, and added many place names to the still misspelt *Verticle Section*.

A remarkable omission is that no faults are shown: these are so common in the Lancashire Coalfield that they must have been well known to Hall as a mineral surveyor. Since Hall was familiar with Farey's analysis of different types of faults (Farey, 1811), it is surprising that Hall did not show any on his map. This is all the more mysterious when, from well before 1831, Hall had been in contact with Adam Sedgwick of Cambridge, who by 1831 regarded him as an authority on this matter (see below). Bagshaw (1846, p. 454) seems to have been the first to record how, at Castleton: *E. Hall has for the last 65 years been a practical geologist, pursuing his favourite study with vigour ... Professor Sedgwick was a pupil of Mr. Hall's in the early part of his geological researches*. Binney noted that: *Hall had been one of the teachers of Professor Sedgwick, who has said that some of his first lessons in geology were from Elias Hall* (Taylor 1862, p. 84). Sedgwick was infamously ignorant of geology when elected to the Woodwardian chair at Cambridge early in 1818 and so set off to educate himself, on his first field excursion, on 30 July 1818. His first destination was Matlock, where he stayed about five weeks, then on foot to Ecton in Staffordshire, then a fortnight at Buxton (Clark & Hughes, 1890). It was surely then that he took these his lessons from Hall, with whom he clearly remained on good terms thereafter.

Elias Hall and the scientific societies

The publication of Hall's Lancashire Map brought him into contact with a wide range of geologists. But he had long before made contact with Sedgwick, who was a corner stone of early activities at the British Association for the Advancement of Science (BAAS). After the first BAAS meeting in York in 1831, the BAAS leaders suggested that Elias Hall be included in an expert group *to collaborate in testing De Beaumont's theory that lines of dislocation of strata* [i.e. faults] *of the same age were parallel* (Morrell & Thackray, 1981, p. 502). In August 1834, Hall wrote to John Phillips, then a leader of the BAAS: *Mr Potter informed me of the meeting of the British Association to be held on the 8th of September in Edenborough* [Edinburgh]. *When and where I intend to produce a plan of the Derbyshire Toadstones, pipe and rake Veins etc and the depth at which the Toadstone is found in the sinkings at different mines. And to speake further on my Geological Map of Lancashire if necessary*. Clearly his Lancashire Map was published by 1834.

On 16 August 1836 Binney went into the field with "Mr. Elias Hall to see the New Red Sandstone rock on the banks of the Medlock" (Binney MSS Notebook p. 22, Torrens Collection). Hall was soon a friend of Binney. In 1837 physician James Black (1788-1867) published a pioneering paper and map of the geology of the Bolton area, which had clearly been inspired in part by Hall's work (Black, 1837).

In 1811 Farey already regarded toadstones as of volcanic origin. But when Hall gave his talk to the British Association at their Liverpool meeting in 1837, he described very minutely the geological development of Derbyshire and exhibited an indented map, cut by himself and suspended from a wall near to a similar map of Lancashire. His abstract stated that *from their regular continuity, it was improbable that the beds of toadstone could be of volcanic origin* (Hall, 1838).

Hall also spoke at the BAAS meeting in Birmingham in 1839, when he exhibited a map of the Central Coal District. Hall gave further papers at the Manchester meeting 1842, when he read *Notices of the Geology of Derbyshire and Neighbouring Counties*, by presenting his models, maps and sections, and at the Cork meeting in 1843 when he exhibited his Map and Sections illustrating Lancashire, and again at York in 1844 when he spoke on *The Midlands Coal Formation*, where he was deservedly complimented by Prof. Sedgwick. In Cambridge in 1845, he gave another *Notice of the Toadstones of Derbyshire*. Of these talks, usually only titles or short abstracts were published by the BAAS, but the antiquary Llewellynn Jewitt (1816-1886) noted at Cambridge that: *Mr Elias Hall of Castleton in our old County, gave a lecture, or rather, read a paper on Derbyshire Toadstone, Whin etc. He is a queer-looking old man, with white hair and lame, and has no notion of lecturing, and he likewise speaks very broad High Peak* (S.C. Hall, 1889, p. 71). It is clear from Hall's comment, *some persons have supposed these toadstones to have been a subsequent formation*, that he still did not understand their true origin.

In 1838 the Manchester Geological Society (MGS) was founded by many of those who had subscribed to Hall's 1834 map. He soon became active at their meetings, reading two papers on the Great Lancashire Coal Field on 31 October 1839. Elias Hall was soon made an honorary member of the Society (Wood, 1987) and gave several further lectures. In 1843 he donated his *Map of Lancashire and a section of the Coal Measures at Gorton Brook*; in 1844 he spoke on the *Coalfields of Yorkshire, Derbyshire, Leicestershire, Lancashire and North Wales*; in 1845 on *The Geology of the Valleys extending from Manchester to Bolton and Bury* (Wood, 1987); in 1846 he lectured on *An Exhibition and Description of a model with an account of the various Strata*; in 1847 he gave *An Account of the Coalfields of Derbyshire and Yorkshire, illustrated by a Geological Map and Sections*. Finally in 1849, presumably using knowledge he had gained at the 1843 Cork BAAS meeting, Hall read *Notes on the Coal Districts of Munster and Tyrone*. No texts of these lectures have been found, though Binney was later able to add much further detail to Hall's knowledge of the Lancashire coalfield.

Hall's Memoir to the Lancashire Map

In 1836, Hall published a 28-page memoir entitled *Introduction to the Mineral and Geological Map*. In it he listed 24 stratigraphic units numbered upwards from the Lowest Millstone Grit Rock to the Magnesian Limestone of Ardwick etc; neither the underlying Limestone Shale and Limestone nor the overlying Red Marls was numbered. Each unit has a brief description and a list of localities of outcrops, and there is a folding chart of eight measured sections of the Coal Measures (Fig. 8); the memoir and sections together demonstrate Hall's intimate knowledge of the coalfield. The printed memoir included comments on faults, which he regarded as helpful in bringing parts of coal seams closer to the surface and reducing inflows of water, but the faults are not shown on his map. Hall continued with calculations of the potential coal resources of Lancashire. The final pages have a list of fossils from the various units compiled by his friend Francis Looney; this includes notes on the superficial gravels and their fossil mammals, both of which Hall had omitted. Binney's surviving notebook for 1835-1840 (Torrens Collection) shows how indebted he then was to Hall's work; this summarises Looney's fossil list, and repeats Hall's stratigraphic column with 25 numbered units, now including the Red Marl.

A third edition of Hall's map was also announced in his *Introduction*. In this, now dedicated to Buckland, Elias Hall advertised copies of his map available for purchase at places in Manchester and London. Prices were £3-3-0 in coloured sheets, £3-13-6 mounted on cloth with bound edges and folded in a case, £4-4-0 on mahogany rollers and varnished, £5-5-0 mounted on a spring roller, plus 5s 0d for the introductory memoir and lithographed key. Hall finally offered his services to *Gentlemen desirous to ascertain the probable value of Coal, Flag, Slate or Ironstone in their estates*.

A second edition of the *Introduction* was published in 1850, with ten pages of a geological appendix to the 1836 version. Hall started with a quotation from a Mr Stewart concerning the volcanic rocks of Hawaii, whose igneous origins Hall compared with the basement rocks of granite, gneiss and mica schist beneath his stratified rocks. This was quoted from Charles Samuel Stewart's book on the Sandwich Islands and his travels in the Pacific, when he visited Hawaii (Stewart, 1828). Hall next listed fossils from the Clay Slate (Silurian) but he confused the fossils of the Transition Limestone (Silurian) with those of the Carboniferous Limestone. Hall discussed the nature of crinoids, and finished with a brief account of fossil reptiles from the Lias and Kimmeridge Clay. A footnote listed fossils from other Mesozoic strata – including a human skeleton in the Chalk! An appendix gave notice of a map he had prepared of the railways of Lancashire. Hall would have been aged 86 when this was published, so perhaps any confusion was age-related.

In a letter to Sedgwick in 1851, Hall noted *having aded a second adition to my Lancashire Geological Map of the coalfield, I thought you would like to have the 2nd addition, if so remit the price by a poast office order*. Any such fourth edition has not been located, but copies may survive in Cambridge, as Sedgwick certainly sent in such an order. After Hall's death, Binney noted how *a good many maps and sections of Elias Hall's are on sale at John Heywood's in Manchester at moderate prices*, nine years after his death (Taylor, 1862, p. 84).

Elias Hall's other maps

Two other maps are thought to have been compiled by Elias Hall. One was of the High Peak of Derbyshire and may have been comparable in part to Farey's unpublished map in the Joseph Banks Collection at the Sutro Library, San Francisco. No example of this map has been located. A Hall map of the Midland Coalfields is also mentioned (Bulmer, 1895), but Croston (1862) said that he was still working on this shortly before his death. It apparently was to include the whole of the South Pennines and all the flanking coalfields. It now seems that Hall may never have completed such a map.

Two letters from Hall to Sedgwick, dated 12 and 21 May 1851 (Cambridge University Library), shed more light. On May 12, Hall wrote: *I have been very busy with my Derbyshire Geological Map since I saw you in Cambridge at the meeting. I have commenced my Survey near Marsden in the N.W. corner of Derbyshire, thence by Greenfield in Saddleworth and Mottram, Hayfield, Buxton, Leek in Staffordshire and Ashburn in Derbyshire, Kirkburton, High-Hoyland, Silkstone, Dodworth, near Barnsley, Sheffield, Chesterfield, Alfreton, Ashover, Matlock, Crich to Bilper, Little Eaton near Duffield, near Derby. This map was the idol of Mr. John Farey, Mineral Surveyor. A section is intended to accompany this map of the coalfield from Ormskirk to Doncaster. If you can give me any information respecting a good Derbyshire map I should be very glad. The Government map of 1 inch to the mile is spoild with shading*. Then on 21 May he wrote: *Respecting my Derbyshire map it has been a long while on hand and I find it difficult to get a Derbyshire map of proper size to lay my manuscript on. It includes parts of Cheshire, Staffordshire, Yorkshire and Derbyshire ... I am very anxious to get the Geology of Derbyshire on paper, before time cloases my carear feeling myselfe decline I cannot expect to remain in vigour long, being eighty six years old on the 6th of January last past*. It seems certain that there was only one such map, which was not finished when old age overtook Hall.

Elias Hall's publications

1824. *A Vertical Section across the great Lancashire coalfield and across the High Peak of Derbyshire.* W. Phillips: London.

1831. *A Geological Section of the Strata across the Coalfield of Lancashire.* [published by Hall?]

1834. *A Mineralogical and Geological Map of the Coalfield of Lancashire with parts of Yorkshire, Cheshire and Derbyshire*. (with later revised 'editions' 1836 to 1851).

1836. *Introduction to the Mineral and Geological Map of the Coalfield of Lancashire.* Love & Barton: Manchester, 28 pp, (with a chart of *Eight Geological Sections and Key to Elias Hall's Geological Map of the Coalfield of Lancashire*).

1838. Abstract: Hall on his Mineral Map of Derbyshire. *Reports and Transactions of the BAAS, Seventh Report (for 1837)*, 91.

1850. *Introduction to the Mineral and Geological Map of the Coalfield of Lancashire.* Slater: Hyde, 10pp.

1850. *Map of the Railways in Lancashire*.

The 1851 census, taken on 30 March, recorded that Elias was then visiting his son John at 35 Radnor St., Hulme, Manchester. But his letters to Sedgwick were sent from Castleton in May 1851. He died there on 30th December 1853. Though so little documentation has survived, he must, latterly have earned a living as a consultant to the many coal owners in Lancashire and so gained his comprehensive knowledge of that coalfield during his professional visits. As a Mineral Surveyor he would have estimated the coal reserves for the colliery operators as well as valuing them for royalty payments to landowners. Most of his publications date from the 1830s when he was aged around 60.

Elias Hall's achievement

Apart from the appreciative remarks made by Binney (1862), others were made by Croston (1868), Cash (1873), Wood (1987) and Cooper (2006); an appreciation also appeared in the High Peak News of August 25th 1900 (Anon., 1900). Hall owed much to Binney. During the MGS meeting on 26 March 1861, Binney was in the chair, when Mr John Taylor junior read a paper on the geology of Castleton. This led the Society to hold an excursion there, and *The Chairman said that this opportunity would be a good one to pay a tribute of respect to the memory of the late Mr. Elias Hall* (Taylor, 1862). In November, Binney was able to announce (Manchester Times, 30 November 1861) that Hall's new gravestone had been erected. Binney next gave a paper on Hall on 30 April 1862, and confirmed that Hall could not have had a memorial tablet in Castleton church, as there was a ten guinea fee for this (Binney, 1862); so instead a gravestone had been placed over his unmarked grave (to which Sedgwick had subscribed).

Elias Hall should be remembered as a pioneer geologist both in Derbyshire and the coalfields of Lancashire.

But he also left records of hitherto unlocated maps, sections and models of the Peak District and Midland coalfields. If any reader has any knowledge of these, please contact the authors.

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Hugh S. Torrens,
Lower Mill Cottage, Furnace Lane, Madeley, Crewe CW3 9EU

Trevor D. Ford,
Geology Department, University of Leicester, LE1 7RH

The last 50 years of mineral exploration in Britain

Tim Colman

Abstract: The last 50 years have seen over 100 British and foreign companies and numerous individuals carrying out mineral exploration in Britain, involving the full and expanding range of geological, geochemical and remote sensing techniques. A number of significant copper, nickel, tin, tungsten, fluorite and baryte deposits have been found, some in areas of little previous mineral occurrences, such as Aberfeldy and Gairloch. Several mines have been opened and others are planned. This account also outlines the complex and sometimes opaque legal framework and the varying support of Government as well as the role of the British Geological Survey.

Britain has a splendid history of metal mining, with Cornish engine houses, the Derbyshire Barmote Court (active since 1287), the great opencast at Parys Mountain and the romantic Dolgellau gold mines. Most metalliferous mineral deposits in Britain (excluding iron ores) occur in the older pre-Mesozoic rocks of the north and west of Britain that are relatively less populated; however, these are the areas containing most National Parks and other forms of environmental restriction to development. In spite of this, more than a hundred domestic and international companies have carried out exploration in Britain during the last fifty years, with the development of modern mineral exploration employing geochemical and geophysical techniques unknown to the earlier explorers. The increase in knowledge of how, why and where mineral deposits form has also enabled exploration to move into new areas based on theoretical considerations.

Mineral rights and access to land

Metalliferous mineral exploration commonly requires access to large areas (tens to hundreds of square kilometres) of potentially prospective land chosen on geological grounds. Access to land is generally less of a problem in countries such as Australia and Canada, but the intensely developed nature of Britain means that there may be many landowners, all of whom have to be consulted for agreement to work on their land.

Mineral rights are complicated. Gold and silver are owned by the Crown and licensing is administered by the Crown Mineral Agent. However, all other minerals, apart from coal, oil and gas, are privately owned, and there is no register of mineral rights. This can create a legal and administrative nightmare. In the late 1960s, Exploration Ventures Ltd, carrying out a major nickel exploration programme in Aberdeenshire, is reputed to have spent around half its exploration budget on legal and access fees to gain legal title to mineral rights.

There is also no legal requirement to declare or record any exploration activities apart from those that may require planning permission. The British Geological Survey, under the Minerals Act 1926, requires the location of any drillholes over 30m depth and has the right to request borehole logs and samples. In Northern Ireland the position is different since the Department of Trade Enterprise and Investment controls exploration through the Mineral Development Act (Northern Ireland) 1969, and issues licences and retains data resulting from exploration activities. A similar act was proposed and almost passed in Britain in 1969, but a change of government led to the bill being dropped.

Government aid for mineral exploration

The Government introduced three programmes of assistance to the mineral exploration industry in the early 1970s to try to mitigate the negative effects of the lack of any sensible mineral rights legislation. All three programmes were funded by the then Department of Trade and Industry, reflecting direct Government support for the minerals industry.

Mineral Exploration and Investment Grants Act

The MEIGA scheme provided for a grant of 35% of allowable expenditure on approved exploration projects for non-ferrous metals, fluorspar, barium minerals and potash. The Act of 1972 was very brief, and the administration of the scheme was through a 22-page document entitled ‘A Guide for Industry’ but known as ‘The Yellow Book’. This laid out the method

***Figure 1**. Environmental considerations are critical to mining in beautiful landscapes, as over the Coed y Brenin copper mineralisation in Snowdonia National Park.*

of application and allowable items which included geological, geochemical and geophysical exploration, rehabilitation of old workings for exploration and testwork for mineral processing. However, general and regional studies, the costs (including legal costs) of acquiring mineral rights and planning permission and any work not related to new exploration (including extending the development of a mineral deposit already being worked) were not eligible for funding. There was also a clause for repayment, with interest, if commercial extraction of any mineral took place within 12 years of last payment. These clauses caused problems of interpretation, and several regional exploration projects were rejected though they would have been very beneficial.

The scheme was initially a great success, with 139 projects proposed in the first three years. There was then a slowdown, with the global downturn in exploration following the collapse of the Australian nickel boom. By the time the scheme closed, 267 projects had been proposed, though not all of them were approved and some withdrawn by the companies before payments were made (Table 1); grants totalled more than £6M. Overall, MEIGA was successful in attracting a wide range of applicants and projects throughout Great Britain (the scheme did not apply to Northern Ireland). It also resulted in a significant amount of exploration data being retained on open file for the nation.

Regional Geochemical Survey Programme

This project started in the late 1960s to develop skills and experience in the newly developed science of geochemical exploration. It was later charged with providing regional geochemical data for a wide variety of elements, to assist the commercial mineral exploration sector and to publish the results as a series of geochemical atlases. It started in Shetland and has now covered Scotland, Wales and much of England with samples at a density of about one per square kilometre. Initially only stream sediments and panned concentrates were collected, but now stream waters and soils have been added, and the emphasis has changed to environmental geochemistry covering more than fifty elements. The project has also evolved into the Geochemical Baseline Survey of the Environment (G-BASE) reflecting this changing emphasis (www.bgs.ac.uk/gbase/home).

Mineral Reconnaissance Programme

Due to the absence of any sensible mineral licensing there was little publicly available mineral exploration data. The lack of information on mineral rights ownership also meant that ‘modern’ mineral exploration, with the investigation of greenfield areas based on favourable geology, requiring access to large areas for the initial prospecting, was very difficult to carry out. The MRP was intended to provide baseline information to fill this data gap to assist mining companies in their choice of prospective ground. It was not specifically intended to locate mineral deposits. Although the first published project of the MRP in 1975 was a gravity survey of Cornwall, most of the projects were carried out in areas that had had little exploration by mining companies and often were in ‘blue skies’ areas. This was a deliberate government policy to encourage exploration in these areas. The early work was reconnaissance, and usually consisted of detailed stream sediment geochemistry accompanied by mineralogy of the panned concentrates. Samples were commonly analysed for twelve or more elements, whereas mining companies then analysed for two or three elements. There were also geophysical projects aimed at proving the utility (or otherwise) of a variety of geophysical techniques in the British environment. Scout drilling was carried out on several projects. A total of 150 projects were completed and published as MRP reports together with 23 Data Releases from smaller or incomplete projects (Colman & Cooper, 2000).

The MRP was intended to cover the whole of western and northern Britain. Publication of the results of the surveys was through a series of Reports that included much of the raw data, including drill logs and with many sketch maps showing the locations of samples and geophysical lines. An early success, which made the reputation of the MRP, was the discovery of the world-class stratiform Aberfeldy baryte deposits, reported in MRP Report no 26 in 1978.

The MRP continued to explore and publish reports through the 1970s and early 1980s, with a budget of around £2.5 million in the late 1970s and a staff of about 30. Its emphasis changed with time. Initially base metals were the main targets, together with a geophysics and geochemistry research programme to demonstrate the most suitable methods for application to British conditions. The upsurge in interest in strategic metals such as platinum and chromium in the early 1980s led to projects devoted to understanding their possible occurrence in Britain. Gold was also added in the 1980s as cheaper analyses with lower levels of detection became available and the gold price rose. The later years were noted by the development of GIS-based techniques of prospectivity analysis, especially for gold. The MRP was subsumed into the BGS Minerals Programme in 1998, where it has continued to develop prospectivity analysis, and has published short reports on various metals and mineral commodities (freely available at www.mineralsuk.com).

	Scotland	Wales	Southwest England	Northern England	Total
Metals	94	22	69	8	193
Fluorspar				32	32
Baryte	5			5	10
Potash				3	3
Total	99	2	69	48	238

Table 1. *MEIGA projects by area and type.*

Mineral exploration since 1960

A variety of base and precious metals have been sought in Britain over the past 50 years, including uranium, copper, tin, lead, zinc, gold and platinum (Fig. 2). A number of industrial minerals, include fluorspar and baryte, are commonly grouped with the metalliferous minerals as they occur in similar deposit types and require similar exploration techniques.

Uranium

A uranium reconnaissance programme by the Atomic Energy Division from the 1940s to the 1960s was originally intended to search for domestic and overseas uranium supplies for atomic weapons. The division became the Radiogeology and Rare Minerals Unit (RRMU) in 1965 and started a five year survey of the uranium resources of Britain in 1968. Northern Scotland rapidly emerged as having the most potential. Some minor occurrences of uranium were found in Cornwall (South Terras mine produced 736 tons of uranium ore to 1910) but small narrow vein deposits did not promise large tonnages. The Scottish exploration used car-borne surveys, with an extending mast containing a scintillometer crystal sending data to analysing and recording equipment in the back of a Landrover. This gave an instant indication of increased radiation and hence the possible presence of uranium.

The Orcadian Cuvette proved to be the most interesting area with widespread low-grade uranium (up to 0.1%) in the Middle Devonian Rousay Flags of Orkney and in phosphatic shales of similar age in Caithness. Sporadic higher values of uranium (up to 0.3%) and thorium (up to 0.5%) were found in fish remains. An RMMU drillhole through a mineralised fault breccia near Yesnaby on Orkney intersected 5.5% Pb & 0.1% U over 0.92 m. This was followed up with two additional boreholes by Rio Tinto Zinc Finance and Exploration (RioFinEx) but was then dropped. RioFinEx also investigated radiometric anomalies in the Ousdale area of Caithness; they drilled over 40 shallow percussion holes between 1971-72, finding up to 300 ppm U over 5 metres in fine-grained uraninite associated with hydrocarbon in arkose overlying the Helmsdale Granite (Gallagher et al., 1971).

Nickel

Minor nickel occurrences were already known in Scotland, at Talnotry in the Southern Uplands and near Inverary in western Highlands. However, the Kambalda discovery in Western Australia in 1966 caused a surge in the nickel price and worldwide exploration. Two of the major mining companies in Britain, Consolidated Gold Fields (CGF) and RioFinEx, independently targeted the major Ordovician basic intrusions of Aberdeenshire. RioFinEx geologists' attention was drawn to a Soil Survey memoir which mentioned very high levels of extractable nickel in two areas (Belhelvie north of Aberdeen over an exposed serpentinised dunite, and an area north of Ellon), which caused restricted growth of a number of crops (Rice, 1975). CGF had undertaken a literature review in early 1967 and concluded that the basic masses of Aberdeenshire could be analogous with the known North American layered complexes of Duluth, Sudbury and Stillwater, all of which hosted nickel-copper sulphides. They began a reconnaissance stream sediment sampling programme in August 1968, and soon realised that RTZ were already drilling at Arthrath near Ellon where a low-grade deposit containing 17M tonnes at 0.21% Ni and 0.14% Cu was outlined. The CGF team also discovered anomalous soils at Littlemill near Ruthven, north of Huntly, where subsequent drilling indicated a smaller deposit of 3 Mt at 0.52 % Ni and 0.27% Cu. These were both too small and too low-grade to be commercial at the time.

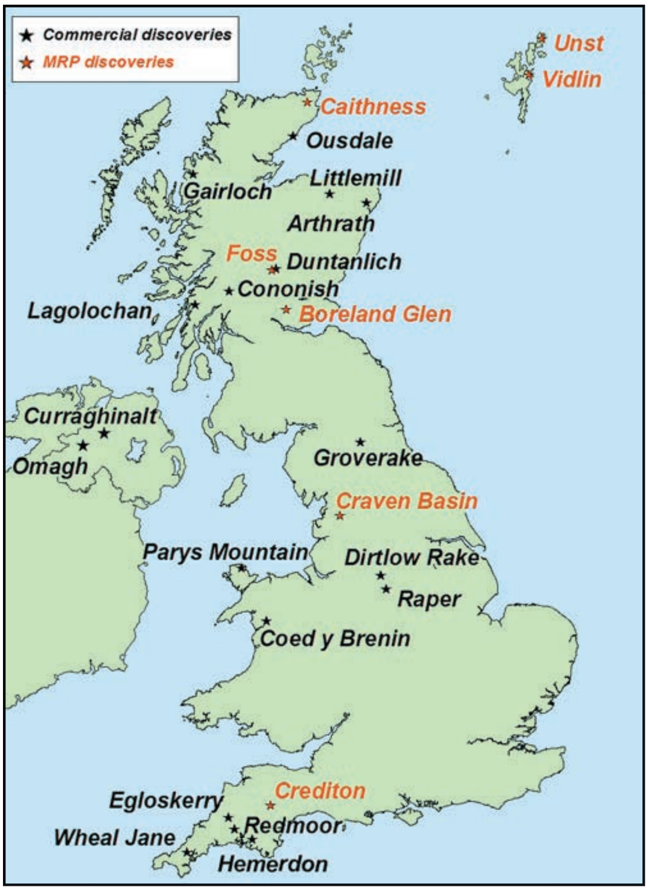


Figure 2. Notable mineral discoveries in the past 50 years.

Initially CGF adopted a prospecting approach, without legal agreements, aimed at covering as much ground as possible and eliminating unfavourable areas. This used a simple exclusive permission to prospect and to grant first refusal in any subsequent negotiations in exchange for a small sum of money. However, RioFinEx secured exclusive prospecting rights over the areas on which they were working. This required landowners to consult their solicitors for advice, an approach that was very time-consuming. However, CGF were forced to follow suit and acquire prospecting rights over the remaining 'open' basic masses of Huntly, Insch-Boganclough and Morven-Cabrach,

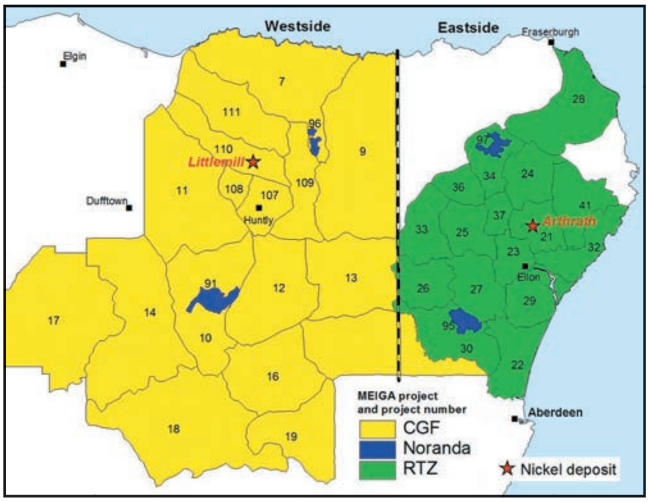


***Figure 3**. Aberdeenshire nickel exploration.*

all of which were in the west of Aberdeenshire. This approach was completely new in Britain as no such wide-ranging basic prospecting had been carried out before. Another major stumbling block was the absence of any publicly available maps of property boundaries and surface ownerships. The geologists had to question hundreds of landowners to persuade them to indicate their boundaries on a map. This again was a very time consuming exercise.

The two companies eventually formed Exploration Ventures Limited (EVL) in July 1969 for the purpose of systematically investigating the whole area for nickel, copper and other metals. EVL split the area along a north-south line from Banff to Banchory (Fig. 3). RioFinEx took the Eastside, including the Arthrath area, while Consolidated Gold Fields took the Westside, including Littlemill. The two companies interchanged all their information while continuing to explore in their separate areas. EVL threw considerable resources into the exploration effort. However, a decision was made in March 1970 to try to locate and obtain legal access and the mineral rights to as much suitable ground as possible, in order to prevent any competitors gaining an advantage. This was partly precipitated by the arrival of Noranda-Kerr, who attempted to sign up landowners in what they thought were the main areas of EVL interest. Only four small areas were obtained by Noranda, in the middle of the EVL area, but it showed the potential for rivals to snap up prospects.

EVL ceased exploration in 1975. The area then lay dormant until the 1990s when nickel prices rose again. Various companies carried out desk studies, but no serious field work. In 2005 a small Irish-based company, Alba Mineral Resources, drilled three holes at Arthrath following reinterpretation of the mineralisation using the then newly discovered Voisey's Bay deposit in Canada as a model. However, the holes intersected the same style of mineralisation discovered by EVL.

Other areas investigated during the early 1970s included the Ballantrae ophiolite where Selection Trust drilled a number of holes but only found minor amounts of nickeliferous marcasite, and the Unst ophiolite in Shetland where Noranda carried out superficial exploration. Around Loch Fyne in Argyll, Consolidated Gold Fields investigated the old Craignure and Coille Bhragad mines for strata-bound Cu-Ni in mineralisation in Dalradian psammites associated with metabasic rocks.

Platinum Group Metals

Platinum, palladium, rhodium, ruthenium, iridium and osmium (all metals of the Platinum Group) have never been worked in Britain. Their presence was not detected until low-cost, low-detection-level analyses were developed in the 1970s. In the early 1980s, the MRP investigated the Unst ophiolite and found high levels (up to 50 ppm) of platinum and palladium (Gunn et al, 1985). Esso Minerals drilled a number of shallow holes in the 1990s, without finding a significant deposit. Occasional grains of platinum group minerals have been found associated with basic or ultrabasic rocks in Aberdeenshire and in the Palaeogene Volcanic districts of western Scotland (Pirrie et al, 2000).

Copper

The last 50 years have seen a number of areas investigated for copper. No significant new deposits have been found in southwest England which was formerly the major producer.

Parys Mountain

Underground mines and large open pits at Parys Mountain, on Anglesey, produced about 130,000 tonnes of copper metal in the years after 1768 (Fig. 4). After lying dormant since the late 19th century, the area has been continuously explored since 1955 by a number of companies (Table 2) and has almost reached a production stage several times. The deposit was considered to be a series of semi-vertical epigenetic 'lodes' in a steeply dipping overturned syncline formed in Ordovician and Silurian rocks (Greenly, 1919). Ordovician shales are overlain by Ordovician rhyolites with Silurian shales at the top of the sequence. Later folding and thrusting has produced a complex faulted syncline (Fig. 5).

***Figure 4**. The great open pit of Parys Mountain.*

year	*company*	*holes*	*metres*
1961-62	Anglesey Mining Exploration	11	3,554
1966-70	Canadian Industrial Gas and Oil	54	14,604
1971-72	Intermine and Noranda	24	5,380
1973-81	Cominco	53	17,338
1985	Anglesey Mining	10	5,925
1988-91	Anglesey Mining (surface holes)	12	2,443
	(underground holes)	125	10,500
1997-98	Anglesey Mining	5	2,200
2005-07	Anglesey Mining	5	2,750
	Total	299	64,694

***Table 2**. The recent drilling history at Parys Mountain.*

Initial drilling was directed at the 'Northern Copper Zone' that consists of series of chalcopyrite veinlets within silicified shales. A resource of 30M tonnes at 0.7% Cu was identified by Canadian Industrial Oil and Gas. British Titan Products also drilled short holes to investigate the area for pyrite for sulphuric acid production. In the early 1970s, other Canadian companies identified the deposit as a member of the volcanogenic massive sulphide class. Significantly, this type of deposit is generally formed almost synchronously with the host rocks and can occur as a series of small to large deposits at a particular horizon. Drilling was therefore directed at the volcanic/shale contact and made significant intersections of 'bluestone' (the local name for a fine-grained mixture of copper lead and zinc sulphides). This was impossible for the earlier miners to separate into the different minerals and so they had largely ignored it, but it commonly forms a significant part of many deposits of this type. However, correlation between drillholes in the steeply dipping and faulted rocks, proved very difficult.

Cominco then took over, and found a new zone of high-grade copper-lead-zinc mineralisation (the Engine Zone) that appeared to be more coherent, but relinquished the site in 1982 after drilling over 50 holes to depths of over 500 m. A retired Cominco exploration manager, Hugh Morris, then formed Anglesey Mining and drilled further holes to demonstrate a resource of 4.8 Mt at 1.5% Cu, 3.0% Pb, 6.0% Zn, 57 g/t Ag and 0.4 g/t Au. A share issue raised over £5 million to fund a major project from 1990 to 1992, including sinking a shaft to 300m and over a kilometre of underground development to produce over 2000 tonnes of ore from the Engine Zone, which was processed in a pilot plant on site. Unfortunately depressed metal prices prevented commercial development. Anglesey Mining carried out further drilling campaigns and used geochemistry to elucidate the volcanic stratigraphy of the deposit (Barrett et al, 2001). There were at least four distinct rhyolite episodes in the Lower Silurian, similar in age to the Skomer volcanic rocks. Only one volcanic episode and a silica sinter known as the White Rock was associated with significant mineralisation (Fig. 5). Other companies have since shown interest in Parys Mountain, but it remains undeveloped.

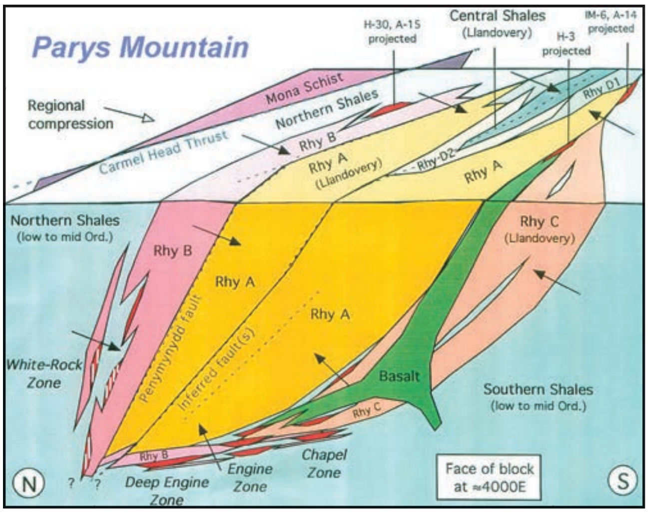


***Figure 5**. Inferred geological structure of Parys Mountain; arrows show younging (by Anglesey Mining, 1999).*

Coed y Brenin

The 1963 discovery of the major porphyry copper deposit on Bougainville, New Guinea, (by a subsidiary of RTZ) generated worldwide interest as it showed that these major granite-hosted copper deposits could be found outside the Americas. RioFinEx carried out a literature search in Britain and found a note on the Turf copper deposit near Dolgellau in Wales: *Andrew Ramsay (1881) stated that it was in this country, more than half a mile west of Dol-y-frwynog, that the once famous Turf Copper Mine was situated in the heart of the talcose schist, which almost everywhere contains much iron-pyrites in small crystals, scattered through the rock, together with specks of yellow sulphide of copper. Very small veins of this ore also intersect the mass. A peat bog occupied the greater part of the bottom of the valley. The turf was pared off the surface and burned in kilns, and being partly saturated with some compound of copper a large residue of valuable copper was left in the ashes. Many thousand pounds' worth were thus extracted.* (Dewey & Eastwood, 1925).

***Figure 6**. Typical veinlet mineralisation at Coed y Brenin.*

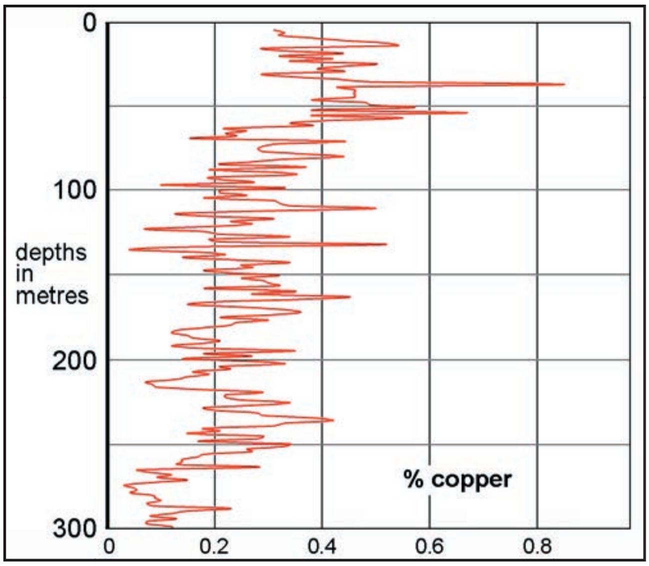


***Figure** 7. Copper values in borehole CB40 at Coed y Brenin.*

RioFinEx carried out a stream sediment survey in 1966 and found a large area with elevated copper content underlain by a late Cambrian granite intrusion with sulphide veinlets (Fig. 6). They acquired the mineral rights and drilled more than 100 holes to depths of 300m, to indicate a deposit of about 200 Mt at 0.3% Cu (Fig. 7). Unfortunately the deposit is entirely within the Snowdonia National Park, and its proposed development rapidly became a cause célèbre with the environmental movement (Smith, 1975). In April 1973 RioFinEx announced that it was doubtful that a mining operation would be economic in the foreseeable future, and dropped the project. Certainly the size is small and the grade is low; Bougainville has 900 Mt at 0.48% Cu and 0.55 g/t Au. During the early 1970s virtually all Scottish granites were prospected for porphyry copper mineralisation. Only one significant area was found, at Kilmelfort near Loch Melfort, but drilling found only low copper values (Ellis et al, 1977).

Gairloch

Remote and sparsely populated following the Highland clearances, the northwest coast of Scotland shelters the small fishing port of Gairloch. Its Lewisian rocks were first mapped by Ben Peach, John Horne and co-workers to produce their classic 1907 Geological Survey memoir with a meticulous lithological description of the rocks (though they lacked modern knowledge of tectonics for their interpretation). They did observe and record a copper-bearing limestone with the words: *a much contorted brown-weathering limestone crops out. It is mixed with talcose streaks and siliceous layers which contain a good deal of pyrite and some chalcopyrite. Its apparent thickness is ten feet but the calcareous portions of the band are probably less than those of the other constituents taken together. None of the pyritous layers exceeds two or three inches in thickness* (Peach et al, 1907). This text became the key to the discovery of the Gairloch deposit over 70 years later.

The area became famous from the late 1950s onwards with the meticulous unravelling of the complex geological history (Park, 1964) to show that there were multiple episodes of sedimentation and volcanism, and at least five periods of metamorphism and structural disruption. Critical to future mineral exploration was the recognition of basaltic volcanic rocks (now amphibolites) overlying the earlier Lewisian basement. However, these structural geologists were not concerned with mineral deposits, and may have actually avoided the conspicuous outcrop by the side of the old track from Kerrysdale to Gairloch. It looked altered, was iron-stained and lacked bedding or schistosity of structural interest (Fig. 8). A Geologists' Association guide mentions a thin marble band within hornblende schists and banded-iron-formation of quartz-magnetite schist in its Gairloch itinerary (Park, 1978).

In the late 1970s Liz Jones, an exploration geologist working for Consolidated Gold Fields, decided to investigate possibilities in the Lewisian rocks. There were few reports of mineralisation in the area and no old workings or trials were known. Initial outcrop sampling showed up to 9% copper, 0.6% zinc, 8.4 ppm gold and 27 ppm silver, but further surface exploration was difficult as no more sulphide-bearing outcrops were visible in the peat-covered terraine. Ten short holes were drilled in 1978, of which six intersected mineralisation at depth. A further 86 holes were then to a maximum depth of 835 m (Jones et al, 1987).

This showed that the mineralisation was within a 4m thick unit of quartz and carbonate, with pyrite, pyrrhotite, chalcopyrite, magnetite and sphalerite giving an overall grade of about 1% copper, 0.5% Zn, 1 ppm gold and associated silver. Total resources were never stated but are probably less than a million tonnes, and there is currently no prospect of further development of the deposit. The surface mineralisation in the discovery outcrop lies in a shallow syncline cut off by a thrust fault. Patient interpretation of the early drilling results traced its downdip extension as a near-vertical horizon plunging to the northwest at about 30^{o}. This appeared to have a distinctively altered and

***Figure 8**. The discovery gossan at Gairloch.*

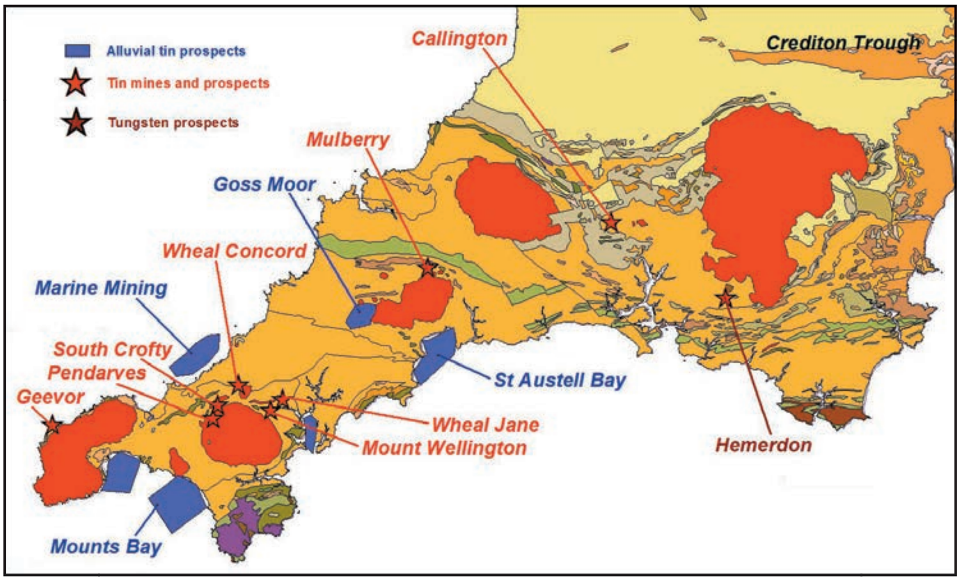


***Figure 9**. Locations of recent developments in extraction of tin and tungsten in southwest England.*

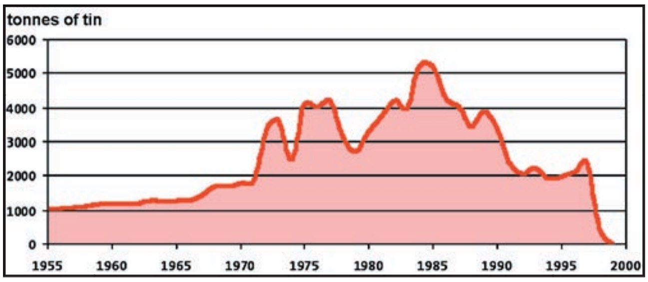
chloritised massive hornblende schist footwall and a more diverse metasedimentary schist hanging wall. It was interpreted to have occurred at the end of a tectonic cycle during an exhalative, fumarolic phase, before renewed volcanism brought fresh lava and pyroclastic debris to the area. The closest analogue to the Gairloch deposit is the Besshi-type Cu-Zn deposit, which forms stratiform lenses in sediments associated with basaltic volcanics. Most of these, including the Japanese Besshi deposit itself, are much younger than Gairloch, which, together with the Outukumpu deposit in Finland, is one of the oldest Besshi deposits in the world.

Another small Besshi-style deposit was found during the early stages of the MRP in Dalradian rocks at Vidlin, near Sullom Voe on Shetland. Drilling a sulphide horizon associated with metabasic rocks revealed low-grade intersections up to 10m with up to 1.2% Cu and 1.1% Zn. Though the sulphide zone appeared to increase in thickness and grade northwards beneath the sea, no further work has been carried out.

Tin and Tungsten

The only area in Britain prospective for tin is southwest England, where cassiterite occurs in fissure veins associated with the Variscan granites (Fig. 9). The area has numerous abandoned tin and copper mines, but by 1960 only South Crofty and Geevor were producing. During the next few years around fourteen companies entered the area as the tin price rose. Exploration was largely restricted to drilling around old mines and opening old workings. Consolidated Gold Fields opened the Wheal Jane mine in 1969. It worked a complex lode with fine-grained cassiterite and sphalerite in pyrite, which had formerly been impossible to separate economically. The opening of Wheal Jane was followed by Wheal Pendarves in 1970 and Mount Wellington in 1976 leading to a considerable increase in tin output (Fig. 10). These deposits were all developed by drilling around old mines from surface, instead of the earlier practice of underground exploration by driving along veins. Between 1967 and 1984 Marine Mining, an American funded company, tried to develop economic recovery of fine-grained cassiterite (that had been released from the old mines) by dredging from the sea bed off Cornwall's north coast

***Figure 10**. Cornish tin production 1955 – 1998 (after BGS Mineral Statistics).*



By 1984 the tin price had risen to $10,000 per tonne, encouraged more companies to investigate southwest England. Geevor Tin Mines, as well as developing their own mine, looked at greisen veins on Cligga Head, a mineralised elvan dyke at Goonzion Downs and alluvial tin at Withybrook Marsh near Bodmin Moor. Consolidated Gold Fields carried out extensive soil geochemistry and shallow drilling around Chasewater, and investigated alluvial tin at Red and Breney Moors. Billiton was actively exploring alluvial prospects in the Carnon River valley, including its estuary at Restronguet Creek, and also over Goss Moor near Bodmin where they found that the 'tin streamers' of the past had extracted almost all the tin. Billiton searched for coarse-grained tin in the floors of the rias (drowned rivers valleys) in St Austell Bay and Mounts Bay. South West Consolidated Minerals raised over £2.5M for exploration around the Callington area centred on the old Redmoor tin mine. They initially drilled the Redmoor veins, before finding a sheeted vein complex similar to the Hemerdon tin-tungsten mineralisation. A series of 30 drill holes totalling over 8000m tested the vein complex to depths of 700m and indicated a 40 Mt low-grade resource at about 0.2% tin.

A small group attempted to develop the Wheal Concord tin mine from 1982-1985 by the traditional

***Figure 11** (Left). Kaolinised granite streaked with dark mineral veins exposed in the small open pit in the orebody of tungsten and tin at Hemerdon.*

***Figure 12** (Right). Cores of mineralised and unmineralised granite from beneath the kaolinised zone at Hemerdon.*

method of crosscutting from an old shaft to find additional lodes. Modern geochemical and geophysical methods can be problematic in Cornwall because of the widespread old workings and non-responsive nature of the mineralisation. They used MEIGA assistance and soon found a promising lode that was mined, but they were unable to withstand the tin price crash of 1985, when tin prices dropped from £10,000 per tonne to £4000. Within 5 years only South Crofty and Wheal Jane remained in operation. Wheal Jane closed and was reopened by RTZ who later amalgamated it with South Crofty, before closing again in 1991. South Crofty followed in 1998, but since 2001 Western United Mines has been attempting to redevelop it as a more mechanised mine.

The major Hemerdon tungsten deposit, which had been worked in the Second World War, was taken up by Hemerdon Mining and Smelting in the late 1960s (Fig. 11). This was run by Bill Richardson, a maverick Canadian entrepreneur who delighted in controversy and whose correspondence regarding other entrepreneurs was robust to say the least: *These fantastic master thieves steal 100% more from the public than the Mafia ever dreamed of*, is one statement in a letter. He sold a controlling interest to AMAX, at that time a major American mining company with its flagship Henderson and Climax molybdenum mines in Colorado. AMAX carried out a programme of intensive drilling and underground bulk sampling at Hemerdon from 1978 to 1982, assisted by substantial MEIGA funding. The ore consists of a sheeted vein complex in greisenised granite intruded into Devonian metasediments known as killas (Fig. 12). AMAX proved a resource if 42 Mt at 0.18% tungsten and 0.02% tin (Fig. 13), and won planning permission for an open pit mine in 1985, before abandoning the project due to low metal prices and changed priorities. The Hemerdon deposit was taken over by an Australian company, Wolf Minerals, in 2007. They carried out some confirmation drilling and sampling, and announced resource figures of 70.92 Mt at the same grades of tungsten and tin, worth £4500 million at prevailing metal prices. In January 2011, Wolf received updated planning permission to open the mine, and is raising finance to commence operations.

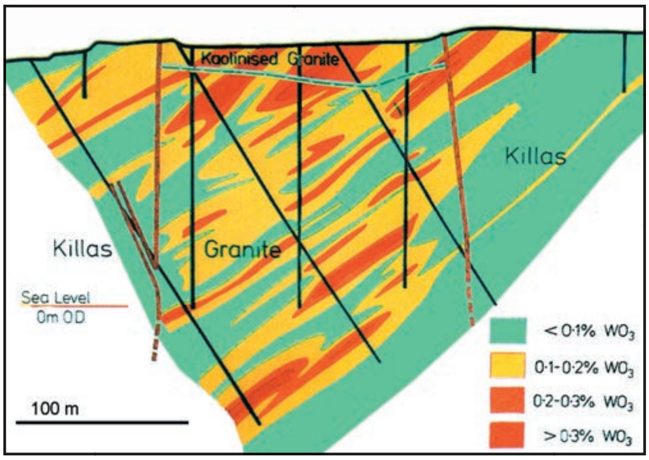


***Figure 13**. Drill holes and tungsten grades through the Hemerdon orebody (after Mining Magazine).*

Lead and Zinc

Attempts at developing lead mines at Leadhills, Nenthead and Matlock all failed in the 1950s. A decade later, Cominco investigated the Carboniferous Limestone adjacent to the Middle Craven Faults west of Malham, in Yorkshire, for replacement deposits similar to those at Pine Point in Canada, but only a few short low-grade intersections were made. In the early 1970s, Central Mining Finance (an offshoot of Selection Trust of London) attempted to drill for deep extensions (at 700-800m) of the major Minera vein in North Wales, but geological and drilling problems prevented the target zone being successfully tested. Discoveries of major lead and zinc deposits in the Carboniferous Limestone of Ireland at Tynagh, Silvermines and Navan encouraged exploration in similar rocks in Britain. The BGS searched reef limestones around Clitheroe in Lancashire for 'Irish-style' mineralisation, but found only low-grade zones of lead and zinc. They were followed by BP Minerals in the early 1980s in the Marl Hill and Brennand areas. Additional discoveries of low-grade mineralisation were made, before BP was taken over by RTZ and the project was dropped. BP and RTZ were also then active in southwest England, where extensive, roadside, deep-overburden sampling explored the Palaeozoic shales for possible sedimentary-exhalative deposits like those in similar rocks at Meggan and Rammelsberg in Germany. RTZ discovered a small deposit with up to 2% combined lead and zinc over 1–2 metres in black shales at Egloskerry near Launceston.

The major baryte deposits near Aberfeldy in Scotland also contain scattered lenses of lead and zinc with up to 10% Pb/Zn. This prompted a major regional airborne survey of the Dalradian belt (already outlined by the MRP) by Exxon in 1983-84, but the project ended before many of the prospects could be properly evaluated. In 1983, a small Canadian company, Domego Resources, investigated the Dalradian limestone area on Islay for replacement mineralisation, but without success.

***Figure 14**. Stope on a fluorspar vein in Ladywash Mine.*

Fluorspar

In 1960 galena and fluorspar were being produced at Redburn Mine at Rookhope in the northern Pennines by Weardale Lead, and in Derbyshire by Laporte Minerals at Ladywash Mine near Eyam (Fig. 14). In 1965 Laporte opened their Cavendish Mill near Stoney Middleton to process ore from its Ladywash and Sallet Hole mines, as well as from various small tributor operations, with an annual capacity of 70,000 tonnes of acid-grade fluorspar, 18,000 tonnes of baryte and 3850 tonnes of lead concentrates. Interest in fluorspar increased in the late 1960s and early 1970s with the development of three new aluminium works in Britain, increased demand from a major expansion of steelmaking and new fluorine-containing chemicals such as fluorocarbons (Smith, 2003). Production peaked at over 235,000 tonnes in 1975 (Fig. 15). In the northern Pennines Blanchland Fluor Mines (a subsidiary of Colvilles Steel) extended its plant at Whiteheaps Mine and also processed ore from Groverake Mine In 1974 Dresser Minerals opened an acid-grade fluorspar processing plant at Hopton in Derbyshire, taking ore from several open-pit operations including the Raper Pit on Long Rake, near Youlgreave. The Italian group Guillini Minerals operated several open-pits feeding ore to Cavendish Mill, and the Clay Cross Company worked open-pits at Milltown and Fall Gate, at Ashover.

There were a number of MEIGA applications in the early 1970s for fluorspar exploration within the northern and southern Pennine orefields. Between 1973 and 1982, Swiss Aluminium had eleven projects, mainly small-scale attempts at rehabilitating and investigating old lead mines to see if any fluorspar had been missed, or drilling along extensions of known veins. Their most important mine was Cambokeels (also known as Cammock Eals) which exploited the major Slitt Vein near Westgate in Weardale. They also bought Weardale Lead from ICI in 1977, and opened a new processing plant at Broadwood, near Frosterley, in 1979. But the fluorspar market declined, and their operations were sold to Minworth in 1982, which collapsed in 1991. Mines on the Groverake and Frazer's Hush near Rookhope continued until final closure in 1998, and so ended mining in the northern Pennines.

Laporte closed Derbyshire's Ladywash Mine in 1979, but continued operations at Cavendish Mill,

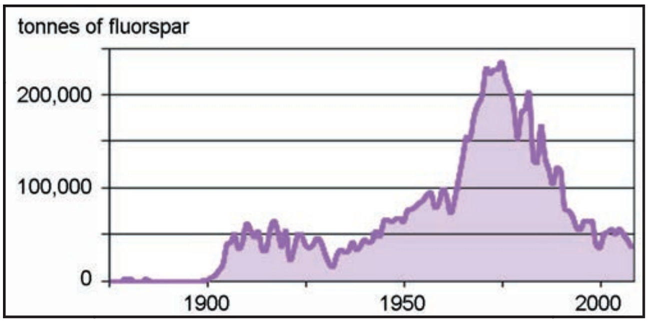


***Figure 15**. Fluorspar production in Britain 1875 – 2008 (after BGS Mineral Statistics).*

sourcing ore from Sallet Hole Mine and numerous tributors. A large replacement body, containing several hundred thousand tonnes of ore, was discovered adjacent to Dirtlow Rake near Castleton in 1984 (Butcher & Hedges, 1987). The limestone had been partly dissolved by acidic mineralising fluids that moved upwards leading to collapse of large blocks of limestone and their partial replacement by fluorspar. Laporte accessed the old Milldam mine on Longstone Edge at the end of the 1980s, but the ore proved unexpectedly siliceous, leading to recovery problems in the processing plant. Glebe Mines took over the Laporte operations in 1999, but ceased production at the end of 2010. With the closure of Cavendish Mill, any small tributors have no domestic outlet for their ore, so this probably marks the end of fluorspar mining in Britain.

Baryte

In 1960 there were baryte mines at Muirshiels and Gasswater in southern Scotland, Settlingstones and Cow Green in the northern Pennines and at Ladywash in the southern Pennines. By 1970, all except Ladywash had been exhausted, in spite of rising demand for baryte in drilling mud in North Sea oil and gas exploration.

In 1975 the governmemt MRP was investigating the 'Pyrite Belt', a pyrite-enriched member (with minor copper) of the Dalradian Supergroup in the upper part of the Ben Lawers Schist (Stephenson & Gould, 1995). Stream sediment surveys indicated enrichment in lead, zinc and especially barium in an area north of Aberfeldy underlain by the Ben Eagach Schist. Checking the area revealed a thick bed of massive baryte with considerable strike length and economic potential. In the 1970s it is unlikely that company exploration techniques would have included barium as an element to be analysed, so the MRP analysis of a wider range of elements was instrumental in discovering the deposit. Eight short boreholes proved the thickness and grade of the deposit (Coats et al., 1978). The baryte mineralisation was shown to be of the sedimentary exhalative (SEDEX) class, based upon a model whereby warm mineralising solutions are circulated within subsiding sedimentary basins and then expelled onto the sea floor along marginal basin-controlling faults. The dense fluid then settles in depressions in the sea bed to form lenses of baryte or massive sulphides (usually lead and zinc).

Figure 16. *Folding in massive baryte in Foss Mine. (Photo: BGS OpenGeoscience).*

This discovery created intense interest, and a number of companies investigated the deposit before Dresser (UK) bought the mineral rights and developed the Foss Mine in 1979, first as a small open pit and then as an underground operation (Fig. 16). The Foss Mine produced its millionth tonne of baryte in 2009. Another, much larger, deposit was found by Dresser in the early 1980s at Duntanlich, a few kilometres east of Foss. This is at the same horizon as the Foss deposit, with intersections of massive baryte exceeding ten metres. Drilling over 30 boreholes proved more than 5 Mt of almost pure baryte. This deposit could have satisfied the demand for baryte drilling mud for the following 30 years, at a rate of 200,000 t/y, saving an annual £10M for imported material. However, planning permission was refused because of the scenic beauty of the area and potential traffic problems. Subsequent appeals with modified proposals have also been rejected by the planning authorities. The MRP found similar, though not economic, deposits at Loch Kandar 40 km northeast of Aberfeldy, and in Glen Lyon 40 km to the southeast. The whole Dalradian belt, from Islay in the southwest to Portsoy in the northeast, is now of interest for the discovery of baryte and lead-zinc mineralisation.

Other areas investigated for baryte include Strontian in western Scotland where Minworth attempted to reopen the historic Strontian lead mines in the early 1980s but were unable to maintain an adequate feed of suitable ore for a profitable operation. And in Cheshire, N L Baroid drilled some shallow holes in 1980 to test a baryte-enriched area of the Sherwood Sandstone Formation at Gallantry Bank near Nantwich.

Gold

Exploration for gold was not considered until the 1970s when the fixed price of $35/oz was removed. The rise to over $800/oz by 1980 encouraged several companies to take out Crown exploration licences. The Australian-backed Caernarvon Gold floated in 1982 and raised £2.5 million to investigate additional potentially mineralised structures around the old Clogau St Davids gold mine near Dolgellau in North Wales. The nearby Gwynfynydd mine was reopened in 1981 as a private venture, and produced around 2000 oz of gold before final closure in 1998.

BP Minerals carried out a major programme over a number of Scottish granites from 1981-84. They were initially interested in the Loch Melfort area where they identified intensive alteration or 'silica flooding' of the granite and country rock associated with elevated gold

***Figure 17**. Gold-bearing quartz-sulphide vein along the roof of the 1985 adit in the Curraghinalt prospect.*

and base metal values. BP, and later RTZ, drilled 37 holes for a total of 6400m on the Lagalochan prospect and found sporadic zones of gold enrichment of several metres exceeding 1 g/t of gold, but were unable to establish a coherent deposit. They also investigated a number of areas in the Southern Uplands around Leadhills and Moffat where the MRP had reported panned gold in a number of streams. These also produced sporadic, low-grade intersections of gold mineralisation. In Cornwall, Britcan (a subsidiary of European Mining Finance) drilled a number of holes in Devonian killas close to the Bodmin granite at Tregeare near Launceston in the late 1990s but without success.

In 1983 the Irish-based Ennex found potentially commercial deposits of the mesothermal quartz-vein type in the Sperrin Mountains at Curraghinalt, near Omagh Co Tyrone in 1983 and at Cononish, near Tyndrum in Scotland in 1984. Curraghinalt, which consists of multiple auriferous quartz-pyrite veins (Fig. 17), was investigated by drilling and an adit (Colman, 2010). The project has recently been acquired by Dalradian Resources, who are continuing drilling to expand the resource.

RioFinEx had been interested in the Tyrone area since the 1960s, and found another mesothermal quartz vein at Cavanacaw, southwest of Omagh in 1985. Drilling showed that this was a complex, brecciated structure up to 5 m wide with some galena as well as gold and pyrite (Cliff and Wolfenden, 1992; Colman, 2010). The prevailing gold price delayed development until 2007, when Galantas Gold Corporation started a small open pit mine with a current annual production of about 5500 oz of gold, 15,000 oz of silver and 250 tonnes of lead. This is currently Britain's only operating metal mine.

Cononish was also explored by an adit and drilling in the mid 1980s along a single vein (Fig. 18); its gold resources exceed 150,000 oz (Colman, 2010). Planning permission for a mine was gained in 1996, but work was held back with the gold price at only around $350/oz. In 2007, following the sustained rise in the gold price and a new feasibility study, the Australian company Scotgold Resources sought planning permission from the Loch Lomond and Trossachs National Park to mine at the rate of 20,000 oz per year, but this was turned down in August 2010 on environmental grounds. Scotgold are currently considering reapplying with a modified proposal. They are also exploring a number of other prospects on their 370-square-mile Crown licence, most of which is outside the park.

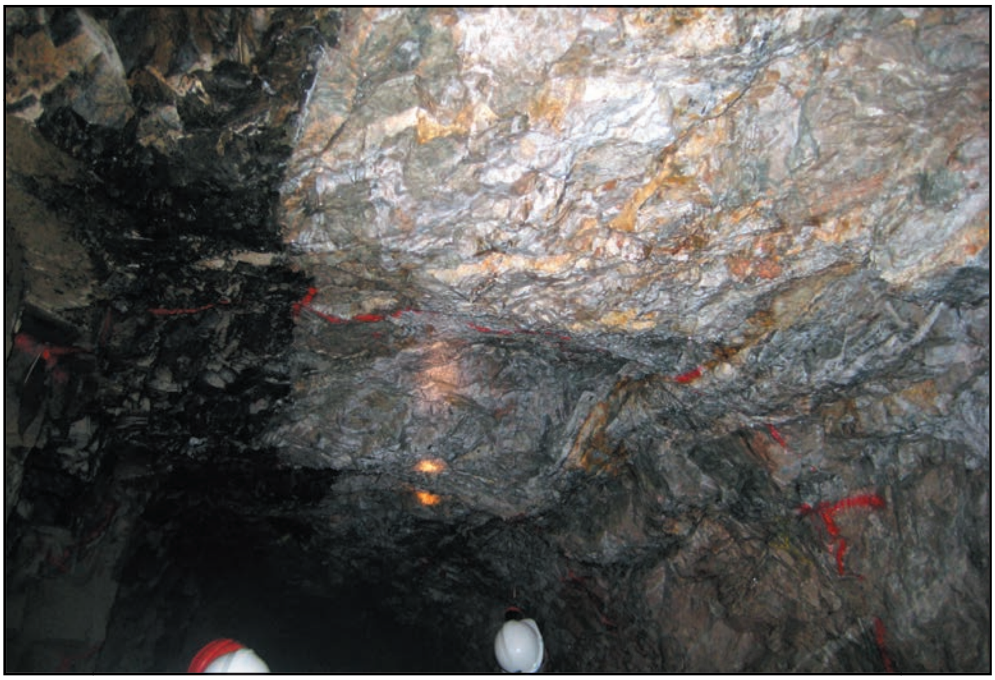


***Figure 18**. Mineralised quartz vein against a dolerite dyke in the roof of the Cononish adit (photo: Gus Gunn).*

A different style of gold mineralisation was found by the MRP in the late 1980s in the Crediton Trough in Devon, which is underlain by Permian sandstones and basalts (Leake et al. 1991; Colman, 2010). Panned gold grains contain platinum and palladium, in a most unusual combination. This is similar to the isolated occurrence at Hope's Nose near Torquay where it is hosted in Devonian limestone. Commercial exploration was carried out by Crediton Minerals, a subsidiary of MinMet (now Aventine Resources), who drilled short holes at a series of locations kept spuriously secret thereby garnering considerable local publicity. Minor intersections of around 2-3 ppm gold were found, associated with carbonate veining in basalt, but no substantial discovery was made, and Minmet dropped their options in the late 1990s.

In the Ochil Hills of Scotland, the MRP also discovered concentrations of gold grains that were traced back to extrusive Devonian volcanic rocks in Boreland Glen. Drilling showed sub-economic (<1 ppm) levels of gold in highly altered basalts and andesites that are indicative of a major epithermal system. Major gold deposits are found in similar high-level volcanic settings elsewhere, mainly in Tertiary rocks that have not been subject to deep erosion. Subsequently a small Irish company, Navan Resources, carried out test alluvial working in the area but did not proceed to commercial mining. A similar setting was found at Rhynie, near Huntly, in Aberdeenshire, when the Devonian Rhynie chert (world famous for its exquisitely preserved early plant fossils) was found to contain anomalous levels of gold arsenic and antimony (Rice et al, 1995). Drilling proved an auriferous epithermal system in unexposed Devonian andesites, but it was not economic.

Into the Future

Fifty years of exploration have discovered a number of mineral deposits; some of which are potentially economic. Furthermore, several styles of mineralisation hitherto unknown in Britain have been found. These include the SEDEX baryte at Aberfeldy, Besshi-style copper at Gairloch and red-bed gold at Crediton. The total value of mineral in the ground of all the significant discoveries, excluding all mining processing and other costs, is estimated to be in the range of £10-15 billion at current metal prices. Much of this, such as the copper at Coed y Brenin, may remain in the ground because of a combination of economic and planning considerations. However, it is probable that several discoveries, notably Hemerdon and Parys Mountain, as well as a number of small gold deposits, will be mined in the near future.

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Tim Colman
Keyworth NG12 5GR
timcolman@tiscali.co.uk

Cool Britannia: from Milankovich wobbles to Ice Ages

Jonathan R. Lee

Abstract: A lecture to the Society outlined recent research that has revealed a long history of multiple glaciations affecting Britain prior to the well-known Anglian event.

The snow and intense cold of December 2010 gave us the coldest month since meteorological records began. It is a timely reminder that despite living in a warm (interglacial) period, the Holocene, climate within recent Earth history has been markedly colder for periods lasting many thousands of years. These cold stages form part of the Quaternary, which spans the past 2.6 million years (Ma). It marks the transition from the sometimes greenhouse climates of the Cretaceous and earlier Cenozoic, through to Ice Age Earth. It is often said that the Quaternary is synonymous with the Ice Age, but this is somewhat misleading. While there were numerous extended cold periods or 'glacials' that did result in Ice Ages during the Quaternary, there were also many warm periods or 'interglacials' where the climate in Britain was at least as warm, if not warmer, than that of today.

Quaternary climate change has had a profound and lasting impact on our landscape. In particular, the form of much of the landscape is a legacy of our Ice Age history. Understanding this history is important in interpreting not just our landscape heritage and its conservation and sustainable use, but also in appreciating just how sensitive our land-mass is to the long-term forces of climate change. This paper explores the long-term history of Ice Ages in Britain and Ireland, focussing on why they occurred, and when and how big they were.

Cenozoic Ice Ages – a global perspective

Global climate has deteriorated progressively throughout the later part of the Cenozoic, with the first Ice Age, or glaciation, of Antarctica occurring as long ago as 34 Ma. In the Northern Hemisphere, such large-scale glaciation first occurred much later. Evidence from core samples collected from beneath the sea bed in the Nordic seas indicate the first presence of glaciers on Greenland during the Miocene about 12.7 Ma ago. The key evidence was thin layers of marine sediment known as ice-rafted detritus. These record the deposition of debris dropped from melting icebergs that have broken off or calved from floating, often marine-based, ice margins (Fig. 1). In simple terms, the detritus provides clues as to the extent of glaciers where land-based evidence such as moraines and till (boulder clay), may have been long-since removed. Geologists can also use a range of geochemical techniques to examine the composition of the ice-rafted detritus to determine which rocks have been eroded and incorporated into the glacier, and indeed, where the iceberg and its host glacier came from – a form of glacier forensic fingerprinting.

Despite evidence for glaciation in Greenland dating back into the Miocene, it wasn't until the Late Pliocene and Early Pleistocene, some 9 million years later, that widespread glaciation occurred within North America, Britain, Scandinavia and the Barents Sea region. Rather than being abrupt, the onset of glaciation was actually a gradual long-term transition that accompanied an increase in global ice volume that spanned a period of about 1.2 million years between 3.6 and 2.4 Ma. Records of ice-rafted detritus from the North Atlantic demonstrate the established presence of large ice sheets on Greenland and around the Barents Sea from about 3.3 Ma. Closer to home, ice sheets in Britain, Ireland and Scandinavia first became active at around 2.7-2.6 Ma. However, between their initial formation and the present day, their extent and the overall scale of glaciation has waxed and waned depending on the prevailing climate and the ability of the ice sheets to grow and maintain their size. Generally though, it has been recognised within the Northern Hemisphere that the scale and frequency of glaciation during the Quaternary cold stages has increased progressively over time.

Now we live in an interglacial – a period where the amount of water locked into the world's ice sheets and glaciers naturally declines, and water previously locked-up as ice within ice sheets returns to the oceans so that sea-levels rise. Since the peak of the

***Figure 1.** Icebergs such as these at Jökulsárlón, in Southern Iceland, are common where a glacier terminates in water. They can leave plough-marks in the geological record, where they are dragged over sediment. When the icebergs melt, its rock debris falls to the sea or lake bed. It may include large erratic blocks, or be finer sediment in discrete layers, and known as ice-rafted detritus.*

last glaciation some 24,000 years ago, the progressive melting of glacier ice in high and mid-latitude areas has resulted in a global sea-level rise of about 130 m. This has drowned large parts of the European continental shelf and brought marine conditions into the North Sea and Irish Sea; both these basins were largely devoid of sea-water during the Ice Ages, when sea-levels were much lower because more water was locked-up within the world's ice sheets. The vast majority of the great Pleistocene ice sheets of the Northern Hemisphere have now melted and disappeared. This includes the Laurentide Ice Sheet, which once covered over a half of North America, and the British-Irish Ice Sheet which has been absent from our landscape for about the past 11,500 years. The majestic fjords of western Norway ,that were once cut by immense rivers of that formed part of the Scandinavian Ice Sheet, are now devoid of glaciers. Ice still clings to some of the high plateaus of western and northern Norway, with Jostedalsbreen the largest, although many of the small alpine glaciers are now in rapid retreat. The largest remaining body of ice in the Northern Hemisphere is the Greenland Ice Sheet. This has a surface area of about 1.7 million km^2, though its margins are rapidly constricting amid concerns of the impact of human-induced global warming. Should the entire mass of the Greenland Ice Sheet melt, it would result in a global sea-level rise of about 7.2 m.

What causes Ice Ages?

One of the most obvious questions is why glaciers and ice sheets have been able to grow so extensively during the Quaternary, and less frequently throughout other parts of the geological record. The precise answer to this question has baffled climate scientists for several decades. The consensus view is that the Quaternary and other geological episodes where Ice Ages have been commonplace are distinctive in combining a specific set of geological and geographic circumstances that accentuates a longer-term pacemaker that regulates global and regional climate.

This climatic pacemaker relates to long-term changes in the shape and nature of the Earth's orbit around the sun. Such astronomical phenomena have forced Earth climate throughout geological time, and have operated over a range of temporal time scales. Critical to our Ice Age story are millennial-scale changes in the Earth's orbit that follow regular and predictable cycles. These cycles are often referred to as Milankovitch Cycles, named after the Serbian astrophysicist who identified them. They correspond to subtle changes in the elliptical shape of the Earth's orbit around the sun (eccentricity) that occur over 100,000 year cycles, and slight tilts (obliquity) and wobbles (precession) of the Earth's axis that occur over 41,000 and 21,000 year time-scales respectively. These cycles impact upon both the amount of radiation that the Earth receives, and the seasonality of its spatial and temporal distribution over the Earth's surface through the seasons.

While this astronomical forcing exerts a dominant control on the background global climate, a range of regional to local geographical and geological controls are also required to enable ice sheets to develop and grow. One of the most important factors is the global configuration of the continents, due to the way it controls oceanic and atmospheric circulation, and in turn the distribution of heat and moisture around the planet. Land is also required in high and mid-latitude areas to enable ice to develop into ice sheets and glaciers.

By way of an example, ice sheets developed on Antarctica far earlier than in the Northern Hemisphere. This occurred when the continent of Antarctica detached from South America about 34 Ma ago and drifted southwards into the Southern Ocean by processes of continental drift. This led to the opening of the Drake Passage so that cold ocean currents then surrounded the Antarctic continent; Antarctica literally froze, and the Antarctic Ice Sheet soon developed.

The story from the northern hemisphere appears to have been more complex. Many scientists believe that the critical factor was the closing of the Central American Seaway that linked the tropical waters of the Pacific and Atlantic, by the formation of the Panama isthmus at about 5 Ma. This was critical because oceanic circulation – a global-scale conveyor belt that circulates water around the world's oceans – is principally driven by salinity differences between these two oceans. With the Central American Seaway open, the transfer and mixing of warm tropical surface-waters between the Pacific and Atlantic Oceans largely balanced the salinity differences between their waters. By contrast, closure of the seaway created a greater salinity imbalance between the two oceans, leading to enhanced global oceanic circulation and the more effective transfer of heat and moisture around the planet.

For northwest Europe and the British Isles, the Gulf Stream plays a key role in keeping our climate more temperate than places such as Labrador and Newfoundland that lie at similar latitudes. Closure of the Central American Seaway led to the Gulf of Mexico becoming more saline driving greater rates of heat and moisture circulation into higher northern latitudes via the Gulf Stream. When these warm saline surface waters are transferred northwards, they cool, increase in density and sink. From the Greenland Sea, these bottom-waters then flow back southwards via the Labrador Sea, drawing even more warm water into the conveyor. Moisture is not only essential in nourishing ice sheets, but it also contributes large amounts of cold freshwater into the Arctic Ocean either directly as snowfall or by rivers from northern Eurasia. Introduction of this cold freshwater into the Arctic Ocean made its surface waters much colder and less salty, making it possible for the regular development of seasonal and continuous sea ice. Extending like a blanket across the oceans in high latitudes and polar areas, this sea ice also played an important role in reflecting incoming solar radiation

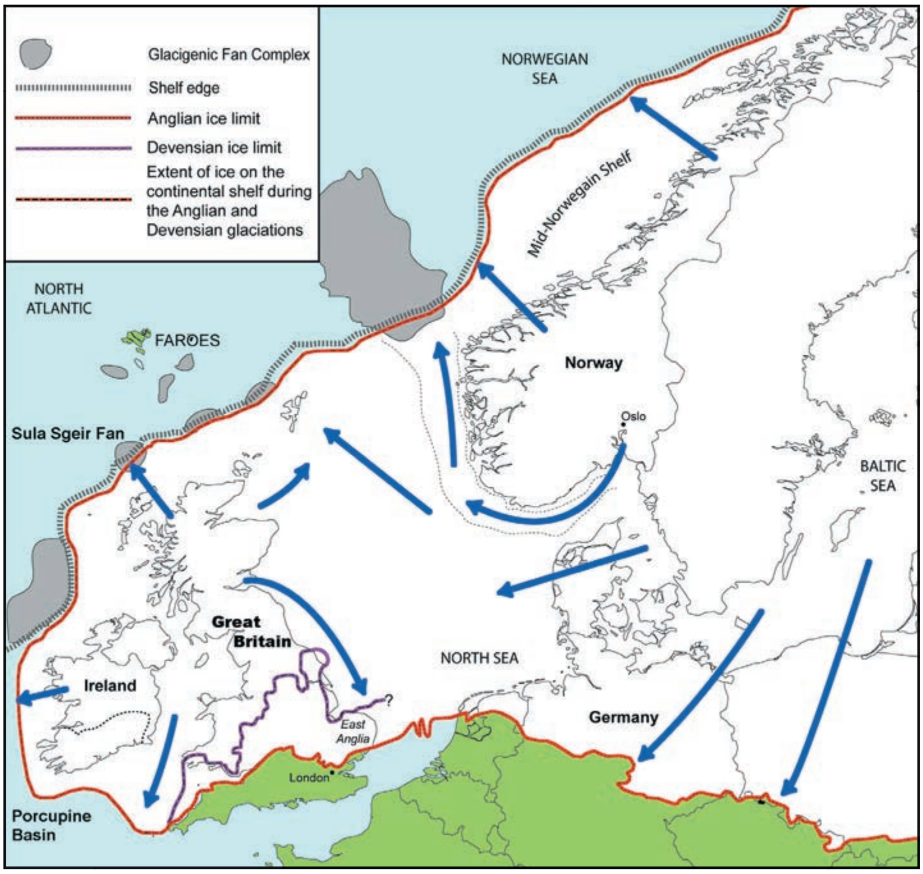


Figure 2. *The main Quaternary ice limits in Britain and Ireland and their extension into Europe, with blue arrows marking the main flow paths of elements of the British-Irish and Scandinavian ice sheets. The coastlines are as they are today, not as they were during the Ice Ages.*

back into space. This process is the albedo effect and is self-perpetuating – the more sea-ice, the greater reflection of solar radiation, the colder it gets, which encourages greater formation of sea-ice…and so on.

Together the astronomical and regional-scale mechanisms regulate climate; they then interact with local geographic factors such as elevation and latitude to control temperature, and so determine whether precipitation falls as rain or snow. These factors in turn drive the mass balance of an ice sheet or glacier – namely, the relative balance between accumulation (the snow fall and conversion to ice that make glaciers grow) and ablation (the loss of ice volume to melting and iceberg calving that makes glaciers shrink). Thus, for an ice sheet to form and grow rapidly, the rate of accumulation has to far exceed the ablation rate. By contrast, if the rate of ablation is far higher than that of accumulation, then either an ice sheet won't form or an existing ice sheet will shrink.

Cool Britannia

Until recently, geologists believed that Britain and Ireland remained ice-free for much of the Quaternary, with only two extensive glaciations during the time (Fig. 2). The first of these was the Anglian Glaciation, which occurred between 0.48 and 0.43 Ma. This was the largest glaciation to affect us during the Quaternary with ice extending across two-thirds of Britain and Ireland, as far south as Oxfordshire and north London, and laterally to the edge of the continental margin from western Ireland round to Norway. Both the North Sea and Irish Sea were land and were occupied by glacier ice. In the Midlands, Pennine Ice deposited the Thrussington Till as it moved west to east across the region. Later, British North Sea ice extended westwards across the Lincolnshire Wolds into the Midlands, depositing the chalky Oadby Till. The second glaciation was that of the Late Devensian, with a maximum ice sheet extent, referred to as the Last Glacial Maximum, achieved at around 27 ka. Again, glacier ice occupied much of the North and Irish Sea basins with ice extending southwards from Scotland into northern England. British North Sea ice reached the Wash but there is no direct evidence for ice ever reaching into the East Midlands. The area that lay beyond the Last Glacial Maximum ice limit, as with other glacial limits, was subjected to intense cold with large areas of frozen ground – permafrost (Fig. 3).

Together, this land-based evidence suggested that Britain and Ireland had a limited glacial history during the Quaternary. It implied that ice sheets and glaciers were only sporadically active within our landscape. This is somewhat puzzling, especially when the position of Britain and Ireland, relative to an abundant moisture source (the North Atlantic) and the Polar Front, is considered. Indeed, new data and re-examined information previuosly published, suggests that Britain and Ireland may have been glaciated on many separate occasions. The evidence for these extra glaciations is often very discrete, and is even open to different scientific interpretations. Equally, determining their precise ages has proved very problematic. A review all of the evidence paints a picture of numerous Ice

Ages (Fig. 4). In broad terms, our Ice Age history can be divided into three separate phases, each relating to different scales and frequencies of glaciation.

2.6 – 1.2 million years ago

The climate in Britain and northwest Europe during this time interval was driven by the short-term precession and obliquity orbital cycles that produced numerous episodes of climate change, albeit of small magnitude and duration. Several scientists have speculated that this global climatic backdrop was probably insufficient to generate permanent ice caps over highland areas of Britain such as Wales, the Lake District and Scottish Highlands, so that when glaciations did occur, they were of limited spatial and temporal extent.

Several lines of evidence have been discovered to support this assertion. On the Hebrides Margin, located to the northwest of the Hebrides, a large submarine fan called the Sula Sgeir Fan extends outwards from the edge of the continental shelf. Sediment cores obtained from the fan reveal that the earliest Quaternary deposits contain fragments of rock derived from northwest Scotland. It is believed that they were transported to the shelf edge by icebergs that then melted and dropped the rock fragments. The source for these icebergs is likely to be glaciers that extended from highland parts of western Scotland into coastal areas, where they eroded and entrained the rock material, before calving and releasing the icebergs. Further south, a number of far-travelled erratics from North Wales, some of which possess glacial striations, have been found within ancient deposits of the River Thames. These deposits date from the early part of the Quaternary when the upper reaches of the River Thames lay within Wales, far beyond their current margins in the Cotswolds. The erratics are considered to have been transported within blocks of ice by melt-water streams that eventually flowed into the Thames. Further downstream, the blocks of ice grounded, whereupon they melted and deposited the erratics. A minimum of ten separate restricted glaciations in North Wales have been speculated.

Figure 3. *Periods of intense cold during the Quaternary resulted in the growth of ice sheets. In areas not glaciated, cold arctic tundra could have looked like this, 24,000 years ago, in what became the southern part of the North Sea.*

Recently, new evidence from the Porcupine Basin, on the continental margin southwest of Ireland, has led scientists to radically reconsider the notion that ice sheets were limited in temporal and spatial extent during this time interval. Sediment cores reveal no less than 16 major pulses of ice-rafted detritus derived from western Britain and Ireland between 2.6 and 1.7 million years ago. Each of these pulses records separate occasions when glacier ice extended into coastal waters, depositing from the melting icebergs thin layers of ice-rafted sediment across the continental shelf and margin. It suggests that in parts of western Britain and Ireland, ice caps were likely to have existed for prolonged phases during this period.

1.2 - 0.48 million years ago

This second period of time extends up to our biggest glaciation – the Anglian. It spans a period where global climate was in state of transition from climate change driven by the smaller, more frequent, precession and obliquity orbital cycles, to the higher magnitude 100-ka eccentricity cycles. The effect of this Mid-Pleistocene Transition (as it has become known), was to make Britain, Ireland and other parts of northwest Europe far colder during cold stages and to reduce seasonality. It pushed the Polar Front further south, and for much longer periods of time led to parts of Britain becoming arctic tundra with the ground frequently frozen into either permanent or seasonal permafrost.

River systems, including the Thames and others that flowed through central and southern Britain, became much more active and dynamic. Not only did they possess a stronger seasonal flow due to melting permafrost and snow, but periglacial slope processes acted to supply them with much greater volumes of sediment. Rivers became more efficient at recycling larger volumes of material along the length of their catchments and over shorter periods of time.

There is also good evidence for an increase in the size and frequency of glaciation. Rather than simply being restricted to highland parts of Britain and adjacent coastal areas, ice also extended into more lowland parts of central England and the Thames Basin, and further eastwards into the North Sea Basin. Evidence from the North Sea and adjacent parts of East Anglia includes several generations of tills and meltwater-incised valleys, iceberg plough surfaces and ice-rafted erratics.

0.48 million – 11 thousand years ago

This time period spans the two big glaciations to have affected Britain and Ireland – the Anglian and Late Devensian glaciations – and the final decay of our last great ice sheet. Globally, the 100-ka eccentricity orbital cycle dominates and drives big oscillations in climate between warm temperate interglacial stages and cold glacial stages; in total, six major cold glacial stages and five major interglacial stages have been recognised.

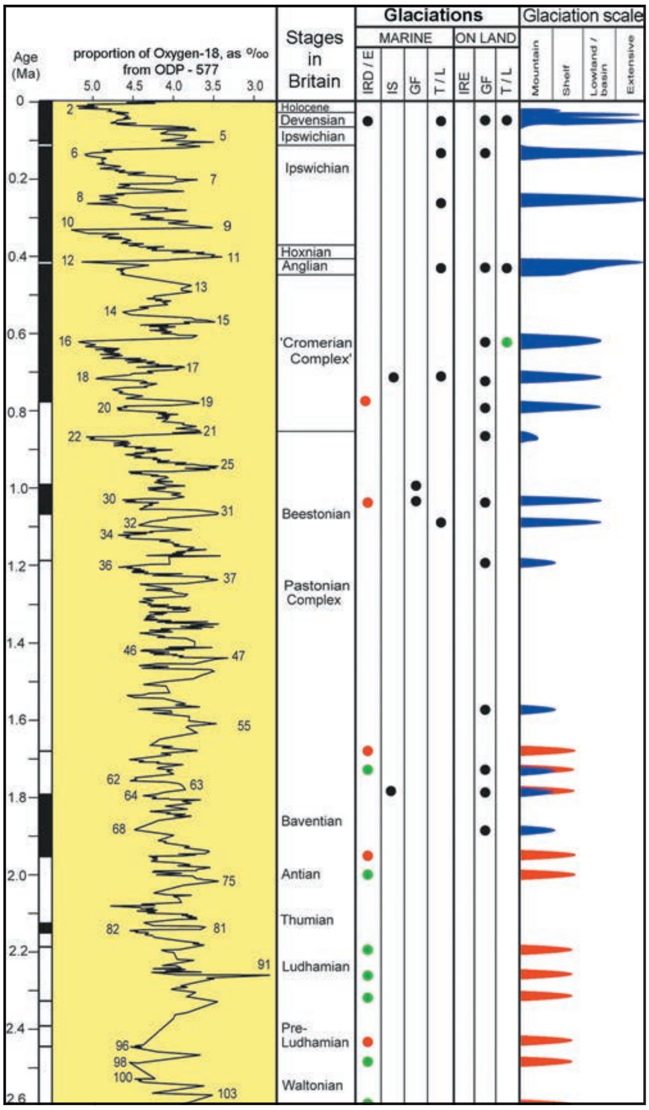


***Figure 4.** Summary of the evidence for glaciations within Britain, Ireland and adjacent marine areas. The line on the left shows an oxygen isotope curve that provides a crude global yard-stick for the volume of glaciation relative to sea-level; peaks to the left show 'glacials' with high global ice volume and low global sea-levels; peaks to the right show 'interglacials' with low global ice volume and high sea-levels. IRD = Ice Rafted Detritus; E = erratics; IS = iceberg scours and plough marks; GF = glacifluvial deposits; T = till; L= landforms. Red spots indicate multiple ice rafting events. Green spots are tentative. On the right, blue bars show the interpreted scale of glaciation, red bars are inferred from the ice rafted deposits.*

During cold stages, the effect of this climate forcing is to promote the rapid build-up of ice volume within high and mid latitudes. Offshore cores and seismic data from around our continental margin demonstrate the presence of glacier ice on the continental shelf during each of the major cold stages. On land, evidence for glaciation is largely confined to the Anglian and Late Devensian glaciations. During the Anglian Glaciation (480-430 ka) the Midlands was extensively glaciated, with the region located some 175 km up-ice (northwards) of the maximum ice sheet extent. The effect of the glaciation on the landscape of our region has been marked. Many of the old pre-glacial river systems were overridden and destroyed, though their host valleys can still be identified buried beneath the modern landscape. Widespread bedrock erosion occurred with vast quantities of sediment removed and deposited either by ice as till or by meltwaters issuing from the ice margin.

Late Devensian ice, although extensive in northern and western Britain and Ireland, the North Sea and Irish Sea, lay just to the west, north and east of the Midlands and did not directly affect the region. Within the Trent Valley, river terrace deposits that relate to this glacial episode contain ice wedge casts; these show that, while glaciers didn't reach the Midlands, the climate within the region was extremely cold and arid, enabling the development of permafrost ground. The maximum extent of the British-Irish ice sheet was reached about 27,000 years ago, with ice extending to the continental margin offshore from northwest Scotland, and southwards to the Isles of Scilly within the Irish Sea. Progressive wasting and collapse of the ice sheet followed, until ice was all but absent from marine areas by 17,000 years ago. The final glaciation to affect Britain and Ireland was a short-lived glacial event called the Younger Dryas, about 12,900-11,500 years ago, during the slow emergence of northwest Europe from the prolonged cold arid climates of the Late Devensian. This caused the growth of the Loch Lomond Stadial Ice Cap in Scotland and the re-appearance of small glaciers in highland areas of Britain. The cause of this short, sharp glacial event is believed to relate to the sudden influx of freshwater into the North Atlantic from Lake Agassiz (which had covered much of the Canadian Prairies) and the collapse of the North American Laurentide Ice Sheet. It is believed that this influx of freshwater disrupted oceanic circulation in the North Atlantic causing the Gulf Stream to shut down and plunging Britain into the deep freeze.

Whether additional glaciations occurred between those of the Anglian and Devensian is unclear. Part of the problem surrounds the interpretation of deposits traditionally assigned to the Anglian and Late Devensian glaciations that may in reality equate to glaciations that took place between the two. Resolving this issue has proved challenging, due both to different interpretations of the same geological information using different techniques, and the general paucity of materials for which absolute dates can be determined.

The wider context

Rather than possessing a limited record for glaciation during the Quaternary, as many scientists had previously considered, the geology of Britain and Ireland reveals a complex history of ice sheets and Ice Ages (Fig. 4). While the precise timing of many of these glaciations cannot reliably be constrained by absolute dating techniques, their broad relative timing and chronology can be determined thorough biostratigraphy and by their

Recommended Reading

Alley, R.B., 2000. *The Two-Mile Time Machine: ice cores, abrupt climate change, and our future*. Princeton University Press. [A highly recommended popular science book about ice core records and climate change; easy to read and to follow.]

Candy, I., Silva, B.N. & Lee, J.R., 2011. Climates of the early Middle Pleistocene in Britain: environments of the earliest humans in Northern Europe. 23-28 in Ashton, N.M., Lewis, S.G. & Stringer, C.B. (eds.), *Ancient Human Occupation of Britain*, Developments in Quaternary Science 14, Elsevier. [Short paper with an insight into the warm and cold climates experienced in Britain in the Quaternary and their relevance to ancient humans.]

Clark, C.D., Hughes, A.L.C., Greenwood, S.L., Jordan, C. & Sejrup, H.P., 2011. Pattern and timing of retreat of the last British-Irish ice sheet. *Quaternary Science Reviews*, in press. [New paper that provides a lengthy summary of the Devensian British-Irish ice sheet.]

Lee, J.R., Busschers, F.S. & Sejrup, H.P., 2011. Pre-Weichselian Quaternary glaciations of the British Isles, The Netherlands, Norway and adjacent marine areas south of 68°N: implications for long-term ice sheet development in northern Europe. *Quaternary Science Reviews*, in press. [Paper that provides a regional overview of glaciations in Britain, the Netherlands and Norway based upon terrestrial and marine evidence.]

Lowe, J.J. & Walker, M.J.C., 1997. *Reconstructing Quaternary Environments*. Longman. [Background book on techniques used by Quaternary Scientists, plus some ideas on the causes of Quaternary glaciations.]

Thierens, M., Pirlet., Lee, J.R., *et al*., 2011. Ice-rafting from the British-Irish ice sheet since the earliest Pleistocene (2.6 million years ago): implications for long-term mid-latitudinal ice-sheet growth in the North Atlantic region. *Quaternary Science Reviews*, in press. [New paper that revolutionises the way we look at glaciations in Britain – many of them and some very old!]

relationship to other geological sequences that possess a crude chronology. The long-term evolution of these events provides a basis with which we can understand the sensitivity of the British and Irish land-masses to climate change throughout the Quaternary.

Prior to 1.2 Ma, there is abundant evidence for the development of ice caps and localised glaciation in highland parts of western Britain and Ireland, and at times these extended onto the continental shelf. In many respects this is unsurprising, considering the abundant supply of moisture from the North Atlantic which in theory would enable ice volume to build up relatively quickly. However, these small orbitally-forced climate changes did not generally promote the development of permanent to semi-permanent ice caps in mid-latitude areas. Nor did they promote the maintenance of a moderate seasonality. In this respect, the inference that ice caps were either permanent or semi-permanent over parts of western Britain and Ireland is unique, and is not replicated in areas such as mid-latitude western Norway. It suggests that the Polar Front lay further to the south than it does today, and/or the moisture input into western Britain and Ireland was sufficient for the glaciers to maintain a largely positive mass-balance despite more moderate seasonality.

From 1.2 Ma onwards, the progressive switch to the longer-term, high-magnitude, orbital-eccentricity cycles pushed Britain and Ireland into the deep freeze during cold stages. The spatial scale of glaciation increased with ice extending occasionally into more lowland and mid-basin areas. Ice masses in Britain and Ireland were able to build-up larger ice volumes more quickly, which was not surprising given the reduced seasonality. A similar picture emerges from ice sheets in Scandinavia, the Barents Sea region and in Greenland and North America, which all experienced more widespread and frequent glaciation. For example, the first shelf-edge expansion of the Scandinavian Ice Sheet and the first known existence of a major ice stream off western Norway occurred at around 1.2 Ma.

By the time of the Anglian Glaciation, at 0.48-0.43 Ma, global climate was driven by the high magnitude eccentricity cycles. This glaciation generally equates to the maximum extent of global ice coverage during the Quaternary. Putting this into a context, the ground where Nottingham now stands lay beneath ice that was more than a kilometre thick. Furthermore, this glacier ice extended unbroken as far as eastern Siberia. From the time of this glaciation onwards, ice sheets possessed an even greater ability to rapidly build ice volume due to low seasonality. In Britain and Ireland, the precise number of glaciations we have had since the Anglian remains contentious.

Together, all the evidence presented demonstrates that Britain and Ireland possesses a long history of Ice Ages and glaciations spanning much of the Quaternary. The scales of these glaciations appear to increase towards the present day, with a series of marked steps in a manner similar to that of other ice sheets that bordered the North Atlantic. It shows that our land-mass was highly sensitive to climate change, and that glaciers quickly became established in highland areas when climate deteriorated.

Acknowledgements

This article has been written as a follow-up to the lecture given by the author to the East Midlands Geological Society in January 2011. It is aimed at a non-expert, general-science audience, and as such omits references to the numerous scientific papers that have been used. However, the author places on record a formal acknowledgement of their contributions to what is a fascinating aspect of the recent history of the British Isles and Ireland. In particular the author acknowledges many individuals who have directly influenced his thoughts and views on this matter, especially Freek Busschers, Ian Candy, Chris Clark, Richard Hamblin, Brian Moorlock, Jim Rose, Hans Petter Sejrup and Mieke Thierens. Steve Booth and Andrew Finlayson are thanked for their constructive and thought-provoking reviews.

Jonathan R. Lee,
British Geological Survey,
Keyworth, Nottingham NG12 5GG
jrlee@bgs.ac.uk

MEMBERS' EVENING, 2011

The fifth Members' Evening was held on 16th April 2011. Once again, the instructions to the presenters were simple: *show us your interests and infect us with your enthusiasm*. It is hoped that other members, especially those who are amateur, will offer short presentations to continue the success of the Members' Evenings into future years.

Escape from Christchurch

Richard Hamblin

Geology field trips can be fascinating and exciting, but one to New Zealand that ends with a Magnitude 6.1 earthquake has to be truly memorable. At the time of the Christchurch earthquake, 21 February 2011, our tour had just ended, and most of the group were in and around the city centre prior to flying home that evening. Sue and I had gone out for the day, and were at the Ferrymead Heritage Park, east of Christchurch, which turned out to be very close to the epicentre (Fig. 1). When the earthquake occurred, we were in an aircraft storage and restoration building, and in retrospect it is surprising that nothing fell on us, considering how much was stored in that building, including items hanging from the roof. The volunteer to whom we were talking, a veteran of the M7.1 earthquake in the previous September, was horrified and estimated this to be at least M8. In retrospect his over-estimate was due to the September event originating 40 km away at a depth of 10 km, whereas in this case he was almost at the epicentre with the focus only 5 km down, so the local intensity was much greater (intensity is the local effect of the earthquake, while magnitude is a measure of its absolute power).

The earthquake

We had no personal experience of such things, but I can say that there was absolutely no warning, no sound before the shock, just a very violent and totally sudden shaking. This shaking felt to be horizontal rather than vertical, and was accompanied by a loud rumbling noise, as well as the sound of Sue screaming. We then encountered our first example of Kiwi kindness that day: almost as soon as the volunteer had finished explaining how to take a back route off the site and look for a taxi on the main road, a chap from the tram shed next door came over to tell us that the manager of the Heritage Park lived in the city centre and would drive us there.

Damage to the building in which we had been standing was surprisingly slight, although a Wessex helicopter transmission system weighing over a ton had moved sideways about a metre, demonstrating the horizontal nature of the movement. Otherwise the only real damage to the site appeared to be quite minor cracks in the paths, but once we got out onto the main road we found more damage nearer to the epicentre. The Heathcote River Bridge was out of action to the north of the park, a train was derailed on the railway bridge south of the park, and we found huge cracks in the roads, with vertical displacements of up to a foot as well as horizontal shearing. However for about three kilometres between the epicentre and the city centre there was very little damage, apart from extensive liquefaction (Fig. 2). Liquid mud had emerging into people's gardens, and through cracks in the road, as a

Figure 2. *A silt volcano built on a grass verge by water and sediment extruded due to liquefaction of the ground when vibrated during the earthquake.*

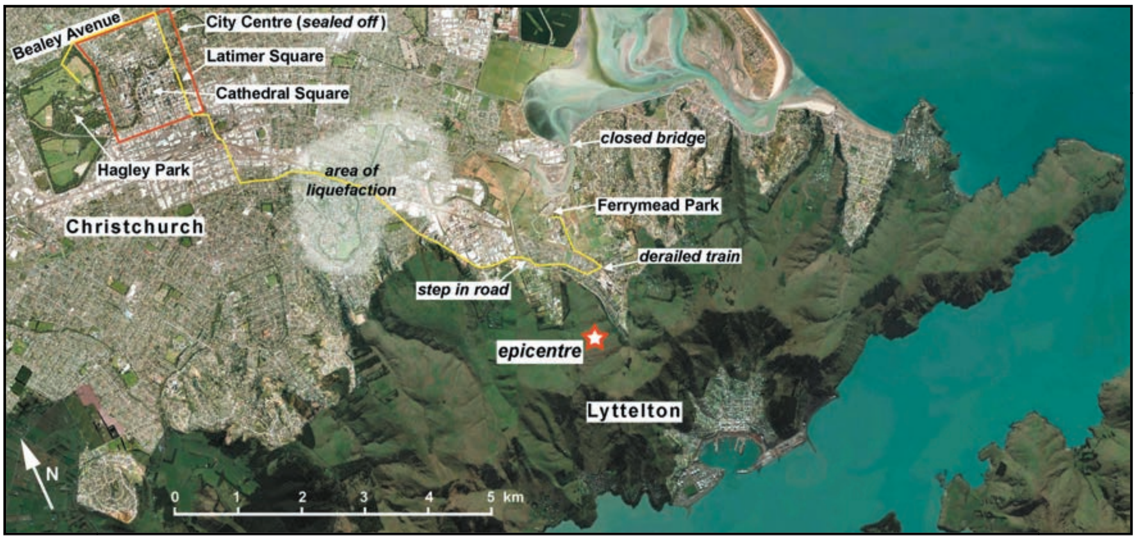


Figure 1. *Satellite image of the area around Christchurch, with the yellow line marking our route back into the city after the earthquake (base image after Google Earth).*

Figure 3. The manager's garden with grey mud expelled by the liquefaction in the foreground, and debris from the two collapsed walls of his neighbours.

result of the city having been built on marshland and the silt beneath the marsh liquefied when vibrated by the earthquake. We were then confronted by some very British understatement: the manager telephoned his wife, who was at their home in the city, and she said that she was unharmed, the house was undamaged, but the garden was a bit of a mess. We assumed that this meant liquefaction, but when we called there the next day, we found that, in addition to liquefaction, the neighbour's side wall and the back wall of the adjacent church had both collapsed into their garden (Fig. 3).

On our way into the city, we listened to the car radio and were not over impressed by the degree of planning apparent. It was clear that all public transport had ceased and that people in the centre were being urged to go home, but they were also urged to keep their cars off the streets! There was no mention of any meeting place for tourists, but it was apparent that people were gathering in Latimer Square, so the manager took us as near there as he could. As we approached the city centre, it became apparent that there was much more damage here, presumably because the thick silty soils beneath the city had amplified the earthquake shock waves. The roads were badly cracked and heaved (Fig. 4), there was more severe liquefaction, and there were floods caused by broken water mains and sewers as well as by the expulsion of water during the liquefaction. There were queues of traffic because all power was off, and we saw our first totally collapsed buildings (Fig. 5).

After sitting in the manager's car for two and a half hours to travel five kilometres we thanked him profusely, and walked the rest of the way to Latimer Square. There were collapsed buildings everywhere, and it did appear that churches had suffered worst, because they are relatively old and just the right size to collapse when subjected to severe lateral movement. Some churches that were not completely destroyed had obviously suffered damage in the earlier earthquakes as well as in the new one (Fig. 6). Most houses in New Zealand are single story and made of timber, so they are safe during earthquakes, but many people had added brick facia walls to their wooden houses, and many of these had fallen away from the main structures.

Figure 5. Total destruction of a brick building along the main road into town.

Figure 4. A road cracked and heaved, and then flooded by a burst water main.

Figure 6. *A church that was damaged by both the earthquakes that struck Christcurch, in February of 2011 and in the previous September.*

The evacuation

It was clear that we could not get back to our hotel, in Cathedral Square, as the whole centre was already sealed off west of Latimer Square. Most of the people in the square were city workers on their way home, and no-one knew where tourists were meant to gather. The authorities were attempting to clear the square, because it was right beside the Canterbury Television building (Fig. 7). This had collapsed and was burning fiercely, helicopters were bombing it with water, and Latimer Square was needed for landing the helicopters. One of the workers sent a text to our daughter for us, to let her know we were alright. On the advice of a policeman, we walked north up Madras Street looking for a motel to put us up, but all we found were more cracked roads (Fig. 8) and more collapsed buildings. Looking across to Cathedral Square, we could see that our hotel was still standing, but the Cathedral looked rather different from how I remembered it that morning (Fig. 9), since the tall spire had completely collapsed (Fig. 10).

When we reached Bealey Avenue the situation was much better, although the roads were still cracked, and we had no trouble getting a room in a motel because all their guests were leaving! We then spent a miserable night in a motel with no power, no water, no telephones working, and a manager who didn't speak English! Having no power or water, we managed to buy some crisps and soft drinks from a corner shop. Aftershocks (which reached up to M5) seemed almost continuous throughout the night as we lay in bed. With each, there was a long, low rumble before the main shaking began, and the next rumble generally started before the shaking had finished. This lonely night in a motel was the worst part of the whole experience. When we met up with our friends the next day, and someone commented how lucky we were to have had a warm bed for the night, I felt that I would rather have spent the night in a tent with the rest of the group.

Figure 7. *The Canterbury Television building in Madras Street, wrecked and then on fire after the earthquake (photo: Mark Mitchell).*

Figure 8. *A cracked road in the city centre.*

When we woke up the world looked brighter but we still had no idea what to do. Would we be able to return to our hotel soon enough for it to be worth waiting on in Christchurch? And would we be able to collect the rental car that was organised, since we didn't have the paperwork with us, we didn't know where the rental company was, and there were still no telephones working. Fortunately by then the road block opposite our motel was manned by the New Zealand Army, who were very friendly and were able to tell us that tourists should go to Hagley Park (Fig. 1). We walked the length of Bealey Avenue, and along the edge of the park. This was the limit of the sealed area of the city centre, with the roads into it blocked by tanks.

In the park there was a lot of liquefaction and cracked paths, and some large trees had fallen (Fig. 11). A tourist evacuation camp had been set up in a marquee that had been erected for a flower festival, and there the Red Cross were organising the evacuation. Air New Zealand and the Air Force were laying on free flights for anyone as far as Wellington, now that the airport had re-opened; and the Salvation Army were laying on food and drink. Considering that this disaster had been completely unexpected, we were impressed by the

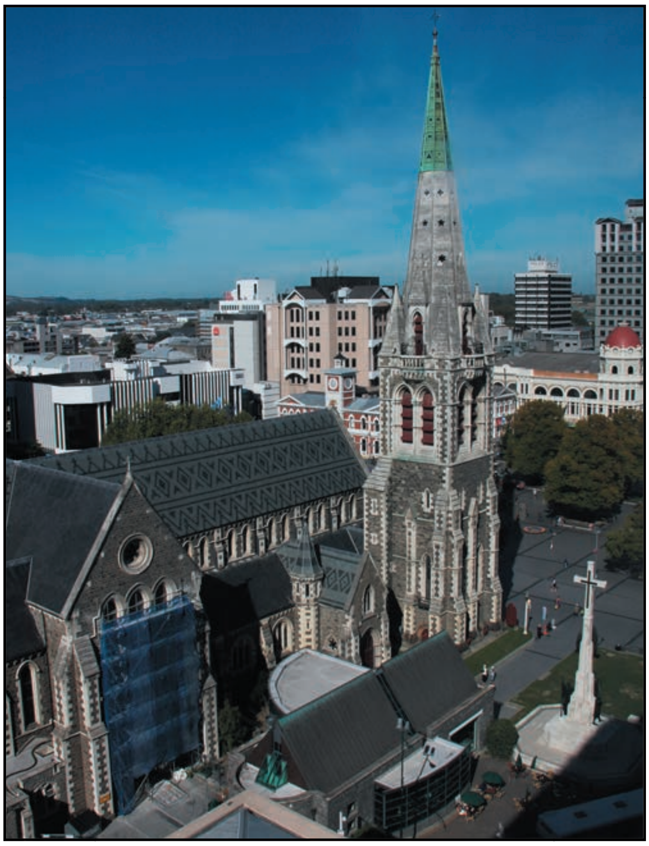


Figure 9. *Christchurch Cathedral before the earthquake.*

efficiency of the official and voluntary organisations, and also by the complete lack of panic. A liaison officer lent us a mobile telephone to ring home and tell them what was happening. If I have to be in another major earthquake, New Zealand is definitely the place to be!

By now it was obvious that we weren't going back to our hotel (where our luggage lay unscathed) before we were due to return home, and we were no nearer to our rental car, so it seemed sensible to accept the offer of evacuation. We were rapidly registered by the Red Cross as evacuees number 1229971, and allocated a flight that afternoon. The only delay was when the Prime Minister of New Zealand appeared on the scene, but we managed to avoid talking to him and go by coach to the airport. At the airport we met up with other members of our group, who we caught up with because the airport had been closed for twenty-four hours. There was some delay issuing boarding cards until it was decided that our Red Cross card would do as a boarding card, and the immigration officials took some persuading to allow passengers through with no ID, but it was not long before we were on our way to Wellington. There we found another Red Cross enclave, which directed us to the Air New Zealand desk. They accepted us as evacuees, and since we were booked on an Air New Zealand flight home, and we did have our passports, they put us on a flight to Auckland that evening.

Figure 11. *Fallen tree in Hagley Park, next to the tourists' evacuation camp.*

Figure 10. *Christchurch Cathedral after the earthquake (photo: Totally Cool Pix).*

In Auckland we found the Red Cross again and they were as efficient as ever. By the time we arrived, all the nearby hotels were full, and they asked us if we were prepared to stay the night with a family who had volunteered to put up evacuees. We were introduced to John and Linda Lewis who put us up in their house on Herald Island for the next two nights. They were both born in England, and we spent our time agreeing how wonderful the New Zealanders are! We telephoned Air New Zealand the next morning and they put us on their flight to London the next day. A number of others from our group were on the same flight, and we met other evacuees, but those people who had lost their passports, including the EMGS Secretary, were delayed in Wellington to be issued with new passports.

Only in June was our luggage rescued from the hotel in Cathedral Square, which is still sealed off.

Photographs on the back cover

Clockwise from the caption:

Remains of the Oxford Terrace Baptist Church.
Collapsed buildings on the edge of town.
The Pyne-Gould offices in the city (photo: Canada Post).
Failure of brickwork on a house (photo: Martin Hunter)
Fractured street near the city centre.
Fissure-style silt volcano created where liquefied soil had erupted along a crack in the road surface.
Landslide caused by the earthquake, at Sumner, east of Ferrymead (photo: Brisbane Times)
Collapsed shops close to the city centre.
Photos by Richard Hamblin except as credited

The Ostracod Fauna of Groby Pool

Katy Gosling

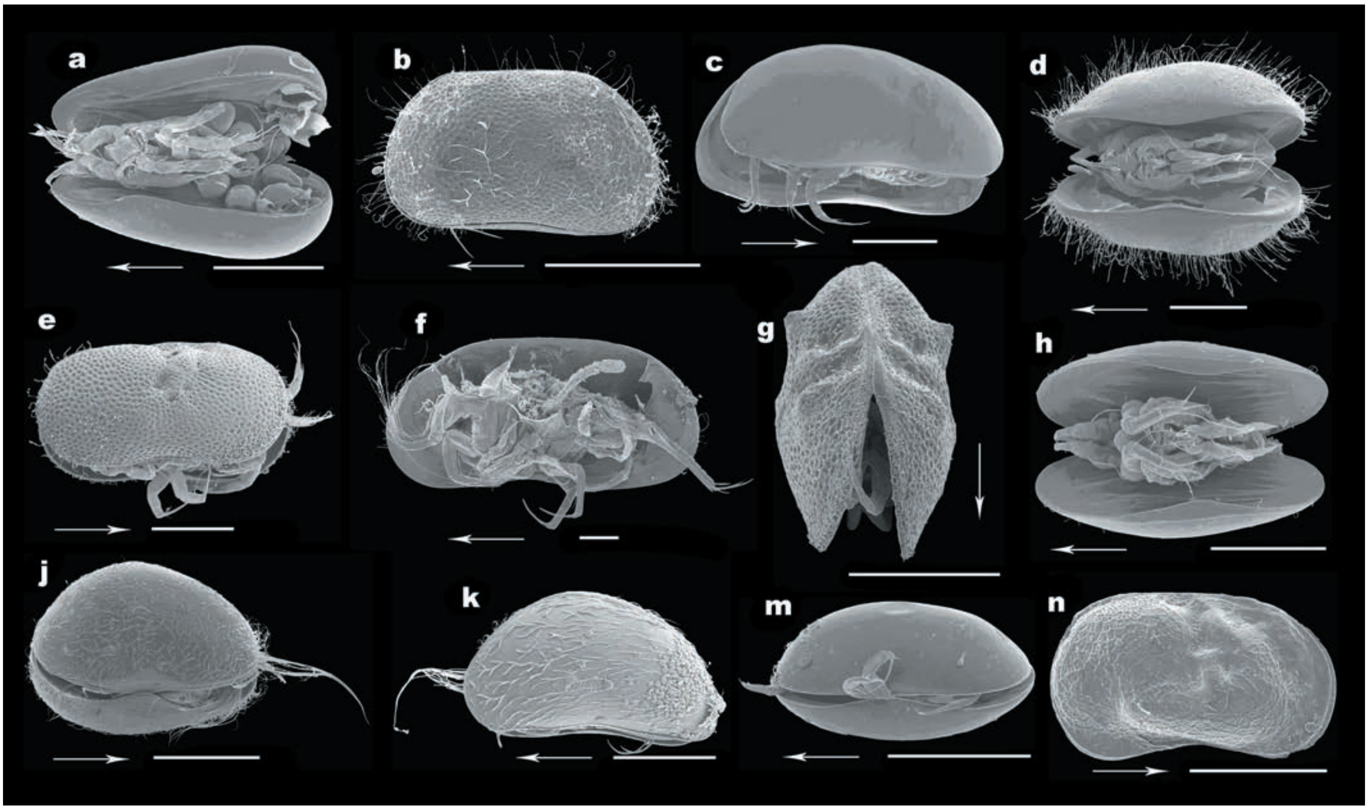
Ostracods are small, bi-valved crustaceans with calcareous valves that hinge above the dorsal region of the body. The valves when closed totally enclose the body and appendages. Their bodies have between 5-8 pairs of limbs, which protrude from the gaping valves and are adapted to swimming, crawling, grasping, cleaning and feeding. Adults typically grow to sizes of between 0.5 and 2.0 mm. They hatch from eggs and moult eight times before adulthood, taking around one month. Many populations are totally female, as they reproduce parthenogenetically.

Ostracods are considered to be the most diverse crustaceans (Meisch, 2000). They can be found in practically every aquatic environment, with some adapted to a semi-terrestrial life. They have the best fossil record of any arthropod, with an estimated 33,000 living and dead species (Horne *et al*., 2002). They can be found throughout the fossil record for the past 500 Ma, from the Ordovician to the present day. Widespread distribution, a small size, and easily preserved calcified valves, mean these microfossils can be found easily. Ostracods have a variety of uses in studies of palaeo-environments, basin evolution, plate tectonics, sea-level changes and modern pollution (Boomer *et al*., 2003).

Groby Pool lies northwest of Leicester and is considered to be the largest natural expanse of water in Leicestershire. It is a natural lake, recorded as far back as the 12th century, and since then it has varied in size. It is currently relatively small, spanning 13.85 hectares, with its greatest depth measuring less than 1.8 m. Groby Pool has been designated a SSSI, due to the richness of the biota living in the pool and in the surrounding woodland.

The aims of the current study were to establish the composition of the living ostracod fauna of Groby Pool, and determine patterns of abundance and distribution among the population. One may question why a geologist would undertake a study of a living rather than fossil fauna. As an undergraduate at the University of Leicester, I had to carry out research for my final year project. Having an interest in micropalaeontology, and wanting to gain experience using specialized equipment, this project proved ideal. During April 2007, the Ostracod Group of the Micropalaeontology Society sampled living ostracods from various sites around Groby Pool. Ostracods were present. Along with training in ostracod identification from Dr David Horne of Queen Mary University of London, this formed a foundation for the project.

Qualitative ostracod samples were collected, by sieving (250 µm mesh size) 10 litres of mixed substrate at each of the six selected sample sites. Each sample



SEM micrographs of selected ostracods. Arrows point towards the front of each; scale bars are each 300 µm (0.3 mm) long.
a *Darwinula stevensoni*, adult female with eggs. **b** *Paracandona euplectella*, adult female. **c** *Candona candida*, adult female.
d *Pseudocandona compressa*, adult female. **e** *Ilyocyprs bradyi*, adult female. **f** *Herpetocypris reptans*, juvenile female.
g *Ilyocypris gibba*, adult male?. **h** *Cypria ophtalmica*, adult female. **j** *Cypridopsis vidua*, adult female.
k *Potamocypris pallida*, adult female. **m** *Candona lactea*? adult female. **n** *Limnocythere inopinata*, adult female.

was processed the same or the next day, to ensure the ostracods did not die before picking. They were examined under a binocular microscope, and ostracods were extracted with a glass pipette. They were easily recognizable by the unique way they swam or crawled. Where possible, 100 live specimens were extracted. Specimens were initially preserved in 30% ethanol to ensure the valves gaped open, to expose appendages. After around 15 minutes, specimens were pickled in 80% ethanol for further study. An additional 100 dried, dead valves were collected from each sample.

Many freshwater species show similar valve characteristics, so it was important to preserve soft body parts to aid identification. The best way to view soft body parts in great detail is to use a scanning electron microscope (SEM) to capture images. However, specimens had to be dry before entering the vacuum chamber of the SEM. Normal drying in an oven would damage the samples by the surface tension and volume changes when liquid turns to gas. The technique of critical point drying was used to dry out the samples, with minimum cell damage. 'Wet' specimens were placed in a pressure chamber, where ethanol was replaced with liquid carbon dioxide. The temperature and pressure were then raised to 31.5^{o}C and 73.8 bar, where the carbon dioxide becomes supercritical and passes from liquid to gas with no structural change that could damage organic tissues. Temperature and pressure were then brought to normal atmospheric levels, leaving dry and intact samples.

The SEM allowed made it possible to view the samples in great detail, and all specimens were identified to species level. Sixteen taxa, from eleven genera, belonging to the families *Darwinulidae, Candonidae, Ilyocyprididae, Cyprididae* and *Limnocytheridae,* were recorded. This roughly accounts for one sixth of the reported ostracod species in Britain. The maximum number of species per site was thirteen. *Cypridopsis vidua* was the most frequently occurring species, found in all six sample sites, and accounted for over 40% of the total live and dead counts. The results demonstrated that ecological factors determine distribution, but many of the species showed wide ecological tolerance, making general distribution patterns hard to recognize.

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A Rock Tour of Scandinavia

Ian Thomas

A Churchill Fellowship in 2009 took the author to study traditional building craft, skills and materials in Scandanavia. It was primarily a learning exercise for future training at the National Stone Centre, but it provided a great opportunity to see some of the geology and stone quarries in the Nordic countries.

The geology of Scandinavia can be summarised as a Precambrian shield beneath most of Finland and much of eastern Sweden, with Norway dominated by the Caledonides. The Baltic islands of Öland and Gotland are almost undisturbed Silurian and Ordovician sediments, whereas Skåne in southern Sweden has Mesozoic rocks. The Oslo Graben is largely filled with Permian igneous sequences. The small Danish island of Bornholm remarkably combines almost all of these elements. Timber is the predominant building material and always has been, but Norway, Sweden and Finland each have about fifty key quarries for building stone. Lime is produced on Gotland and in Denmark.

Norway has two main clusters of activity – in the Fjordlands between Trondheim and Bergen, and around Oslo Fjord. Larvikite (on the south coast) dominates national production, followed by flagstone (quartzite at Oppdal and Alta), black phyllites (at Otta), and granites (notably at Iddefjord). A wide variety of other rocks that are also worked include soapstone, marble and slate. In Trondheim, the Nidaros Cathedral is remarkable for the sixty sources of its ornamental stonework. Soapstone is dominant, but others include sandstone, dolomite, marble, greenschist, granite, syenite and gneiss. Not far south of Trondheim, the old copper mines at Løkken and Røros are heritage sites (the latter has World Heritage status), and Oppdal has quarries in cleaved quartzite.

In southern Norway, large quarries near Larvik each produce different varieties of larvikite. Almost all the building and decorative stone is exported, with about 80% of it going to China and then as finished products to the USA and Europe. Of the larvikite that doesn't reach the quality for making worktops or cladding stone for shop fronts, blocks weighing 20-60 tonnes are loaded directly onto barges for despatch to coastal defence sites, including many in Britain. On the southern border near Fredriksborg is one of the few remaining, traditional, monumental workshops, and one of the nearby islands has a community-run granite museum.

Denmark has historically been dependent for stone on her former Baltic territories such as Gotland. Hard rock is confined to the island of Bornholm in the southern Baltic, but production is now almost nil. What was a granite industry at Mosseløkken now mainly delivers education in heritage skills.

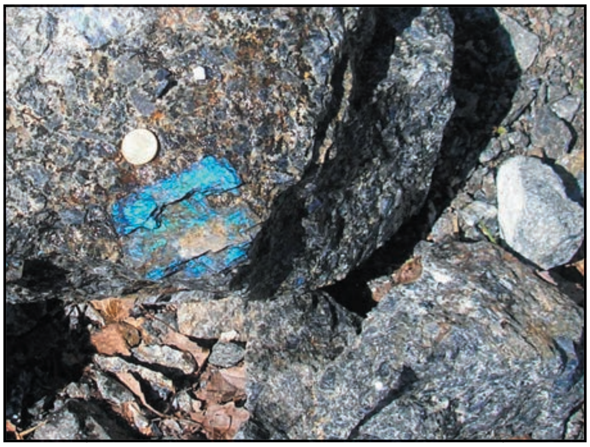
Sweden has most of its stone industry based in the southern quarter of the country, especially around Kristianstad, on the Baltic islands and along the west coast. Most stone, including that from an active diorite

A coastal quarry producing larvikite in southern Norway.

quarry near Boalt, is used domestically or within Scandinavia. The Baltic islands of Öland and Gotland have more than their share of the stone industry, with shallow extraction of sandstone on both and an important lime industry on the latter. On Gotland, Visby is a centre of the modern lime industry and was once noted for its building stone; it has many very large and mainly derelict churches built of limestone. A local industry in green marble is just surviving, though most of its former quarries now host tigers in a safari park.

Finland has most of its stone industry in the southern half of the country, and this has grown significantly over the last twenty years. Granite is worked mainly in the southwest, notably at the massive quarries of Balmoral Red granite. Further northeast, at Lappeenranta, extensive quarries extract rapakivi granite and supply processing works nearby. In contrast, very small quarries, some only metres from the Russian border near Ylämaa, produce spectrolite, an iridescent variety of labradorite feldspar prized as a semi-precious gemstone. It occurs in rafts of anorthosite within a small batholith, and is largely produced from very selective, one-man quarry operations. A soapstone industry in central Finland works deposits of talc-magnesite-greenstone. The forts of Soumenlinna, at Helsinki, are a national treasure maintained by prisoners training as masons.

Choices of natural stone are dictated by price, aesthetics and the ability to deliver, but some decisions have been controversial. In Helsinki, there is flexing and potential failure, under the sub-Arctic conditions, of the panels of Carrara marble used on the Finlandia Concert Hall. Now there is controversy over the potential use of Carrara marble for cladding and roofing the Norwegian National Opera House. The main types of stones used originally in Sweden's Royal Palace in Stockholm were Roslagen Sandstone from the north of the city (now either exhausted or built over) and Gotland Sandstone (which some claim poses technical issues); the Palace is in need of restoration, but national pride may not accept the use of German or British sandstone. By contrast, the Danes lost their original building stones when Gotland was ceded to Sweden in the seventeenth century, and they have had few qualms about restoring the Amalienborg Palace using imported stone.



The iridescence of spectrolite shows in a loose block on a quarry floor near Ylämaa in eastern Finland.

A small quarry exposes the spectrolite.

EXCURSION

The Matlock Gorge

Leaders: Lynn Willies, assisted by Colin Bagshaw

Sunday 10th October 2009

The aim of the excursion, attended by some 30 members, was to study the geology of the Matlock Gorge and its associated topography and lead mining history. The latter is well documented in *Lead Mining in the Peak District*, edited by Trevor Ford and Jim Rieuwerts and published by the Peak District Mines Historical Society in 2000. The rock exposures encountered are all within the upper part of the Carboniferous Limestone sequence and may be summarised as in Figure 1. Most of the excursion area is covered on both the BGS Chesterfield One-inch map (Sheet 112) and the Matlock geological map at 1:25,000.

The excursion began in the public car park adjacent to the Sainsbury's store, alongside the new stretch of the A6, which by-passes the old road bridge in the centre of Matlock. From here can be seen, looking south beyond the supermarket, an old quarry face that displays a series of limestones dipping gently southwards. These belong to what is referred to as the Cawdor Limestones on the BGS Sheet 112, but now have been renamed as the Eyam Limestone.

After walking west to a point about 200 m along the new road (Cawdor Way), the party viewed the exposure just to the west of the old railway line. These rocks are lower in the sequence and belong to the Matlock Group, now renamed the Monsal Dale Limestone; they tend to be more massively bedded than the Eyam Limestone, and are somewhat paler in colour. At the base of this section is the amygdaloidal basalt of the Matlock Upper Lava. Do not be deceived by the fine black mesh of the safety netting that is holding back the badly decomposed clay wayboard at the top of the lava. The lava has weathered to a rather pale colour and from a distance has a similar appearance to the limestone.

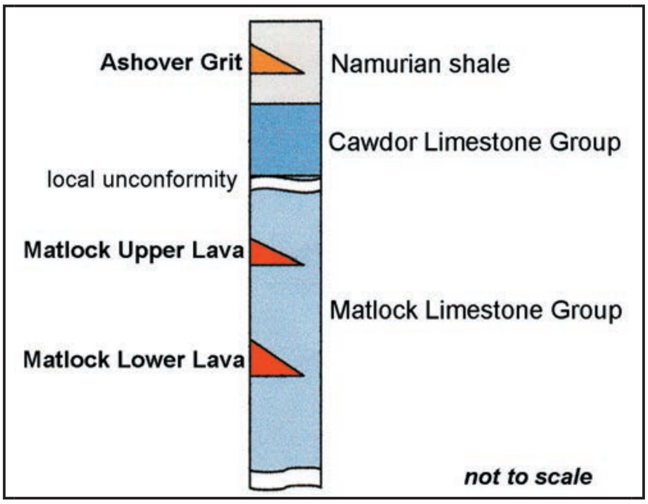


Figure 1. *The geological succession in the Matlock Gorge.*

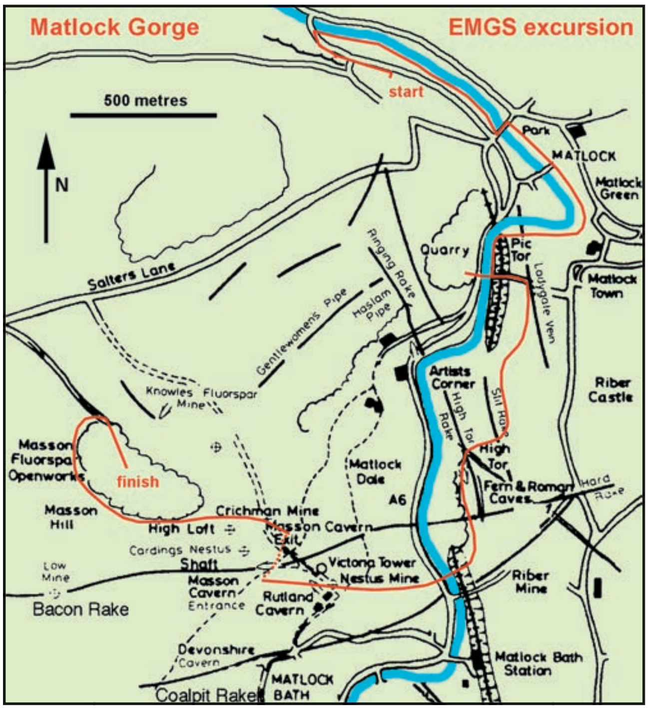


Figure 2. *The excursion route (adapted from Ford and Rieuwerts, 2000).*

The route continued a further 100 m to the northwest before turning sharp right along the path leading southeast along the right bank of the River Derwent. Beyond the end of a high retaining wall, the river bank widens out to reveal poorly preserved remains (including a low wall and disturbed ground) of old lead mine workings of at least 200 years ago. This area and the bank opposite are riddled with such workings, as well as underground passages and drainage levels (soughs). Some of their exits can be seen on the far bank, including one where iron oxides are being precipitated when anoxic ferrous solutions come into contact with the oxygen of the atmosphere.

The path continues to the southwest end of the old A6 road bridge (Fig. 2). Cross the bridge, and enter the recreational park situated on the floodplain at the confluence of the Derwent and streams draining from high ground to the northeast. By the entrance to this park is a memorial about 2 m high, constructed of local gritstone that demonstrates a variety of textures typical of the local rock.

The path alongside the river was followed to posts at the end of a bridge, which recorded the staggering water levels that flooded the town in the 1960s. Continue to just beyond a children's play area and take the path to the right signed Pic Tor, crossing a stream that was partly responsible for the town flooding, and turn right again past the flood defence structure. Just beyond, by the side of the path, well-bedded, fossiliferous, cherty limestones dip to the east and rise westwards to drape the massively bedded 'reef' or 'mud mound' of Pic Tor. Such structures are common in the Cawdor Limestone, and the reef has been incised by the river to produce a spectacular vertical face (Fig. 3).

Figure 3. *The vertical face at the foot of Pic Tor, viewed from the northwest.*

Further west the Tor is cut by the Ladygate Vein, which was worked for lead ore in the 18th and 19th centuries. An information board explains how the mine was powered initially by a water wheel, on the far bank of the Derwent, which was connected to the mine by wooden rods. Later, it had the first steam engine to be installed in the Peak District. Alas, only small amounts of ore were ever recovered.

On the way south, a small detour was made across the Derwent to view the face of Harveydale Quarry where beds can be seen dipping steeply southeast towards the river. South of the bridge, rapids are formed where the river crosses the outcrop of the Matlock Upper Lava. The party returned eastwards to the Pic Tor road and began the ascent of High Tor. The road is followed as far as the first houses, where a sharp right turn leads into the High Tor Grounds, which were originally developed by a grandson of Richard Arkwright as a pleasure area for visiting dignitaries.

Soon there are views of the more level ground of Namurian shales to the east (left), beyond which is the Ashover Grit ridge on which Riber Castle stands. Various stops were made on the ascent to admire the views, particularly the face of Haveydale quarry which displays the unconformity between the Matlock Limestone and the slightly undulating Cawdor Limestone above.

Close to the summit, old workings in High Tor Rake were examined; and from a nearby viewpoint could be seen the steeply dipping limestones on the opposite (i.e western) side of the valley. It was explained how these were responsible for the uniclinal shift of the valley and for major landslips along bedding planes. One such slip occurred in the 1960s and blocked the A6 for several weeks. To the southeast, the extensive landslip in the Namurian shales near Starkholmes was also pointed out, as was the Ashover Grit scarp of Black Rocks in the distance to the south.

The morning concluded with the descent to the cable car station adjacent to Coalpit Rake. The more intrepid members of the party took the path signposted Giddy Edge along the near vertical face of High Tor, while others descended more sedately. It is with some relief that we report that all arrived safely at the cable

Figure 4. *The eastern face, about 15 m high, of the Masson Hill open pit; the Matlock Upper Lava is at the top right corner of the face.*

car, and were able to enjoy the spectacular views along the valley on the journey up to the Heights of Abraham, where lunch was taken at the various tourist facilities.

The afternoon began with an underground tour of the Great Masson Cavern, which is part of the extensive old lead mining complex that honeycombs Masson Hill. Lynn Willies, led the group along the tourist route pointing out many features of interest. The party was also taken into the workings of the Black Ox Mine, not normally open to visitors; these were developed to exploit minerals such as galena, fluorite, calcite and baryte deposited in partially dolomitised limestone along the Great Rake, also known as Bacon Rake.

The geology of the mineralisation is complex. Some minerals were in primary deposits within fractures, but the country rock has undergone extensive solution, mainly in Pleistocene times. The resulting caves then became sites for deposition of mineral grains washed in from elsewhere. For information on this, a good starting point is *Lead Mining in the Peak District*, cited above, or a visit to the Mining Museum in Matlock Bath.

The view from the mine exit was east across the valley to some of the morning's localities, particularly the 'reef' of High Tor and the extension of the Great Rake that forms a vertical feature within it. The party followed the track east and, where it turned right down the hill, left its path and ascended diagonally towards the northwest. An outcrop of Matlock Upper Lava with amygdaloidal texture was examined.

The walk continued to the very large Masson open pit (Fig. 4), which was a source of fluorite until about 1980. This working was in an ore flat between the Upper and Lower Matlock Lavas, which here are about 15 m apart, as these relatively impermeable rocks controlled the movement of mineralising fluids. The Upper Lava is the highest rock exposed in the quarry and the Lower Lava forms the floor, while the rich mineral deposit was sandwiched between them. The quarry may be entered from its northern end, near which are loose blocks containing the fluorite-rich mineralisation.

The party then retraced its steps to the cable car, making sure not to miss the last descent, and returned along the valley to the starting point after a packed and exhilarating day. Our leader was thanked for his excellent work in preparing and leading the excursion and for sharing his expertise with members.

EXCURSION

Clitheroe Reef Belt

Leader: Neil Turner (Wollaton Hall Museum)

Sunday 9th May 2010

The day was sunny and dry for meeting up at the Nick O' Pendle, on the road over from Clitheroe to Sabden. After a look at the geology map of Clitheroe, spread out on a bedding plane slab, the group climbed the hill at the side of the road cutting to see the view of Clitheroe and the Ribble Valley. The row of reef knolls stretches from Clitheroe Castle via Salthill and Bellman Park Quarry to the largest of them all, Worsaw Hill (Fig. 2). Nick O' Pendle was a glacial meltwater channel during the Pleistocene. The Bowland Fells were in clear view, and even Blackpool Tower could be identified.

Within the Craven Basin, the Bowland Sub-Basin is surrounded by a number of highs that were rigid blocks subsiding more slowly. To the south is the Central Lancashire High, to the northeast the Askrigg Block, and to the northwest the South Lakeland High. Lower Carboniferous marine sedimentation began on a shallow carbonate shelf or ramp that was subsequently fractured into the series of highs and lows within the basin. Although subsidence in the Bowland Sub-Basin started relatively uniformly, while the Chatburn Limestone was being laid down, it increased and became more uneven, which led to the development of deep water Waulsortian mud mounds of Tournaisian age. The Waulsortian mud mounds (previously referred to as reef knolls, knoll reefs or reef limestones) at Clitheroe are older than these in Derbyshire, but are thought to be roughly the same age as those in Ireland. After formation of the Waulsortian mud mounds, the Visean saw a switch to the hemi-pelagic Hodder Mudstone Formation. As the basin continued to subside it became deeper and more anoxic. When the surrounding apron reefs at Malham, Settle and Cracoe became established,

Figure 1. *Limestone seat with tiles of crinoids at locality 6 on the Salthill Quarry trail where fossil crinoids have been commonly found (photos: Richard Hamblin).*

Figure 2. Worsaw Hill, largest of the Waulsortian mud mounds in the Clitheroe area.

skeletal carbonate input into the basin largely ceased, as marked by the pelagic Hodderense Limestone. The Pendleside Limestone marked a return to limestone turbidite, with its many debris flows derived from the surrounding carbonate shelf. The succeeding Bowland Shales were laid down before a delta spread southwards and the Pendle Grit was deposited.

Pleistocene ice moved southwest down the Ribble Valley, leaving behind over-steepened hillsides, as at the northern side of Longridge Fell, valley floors filled with glacial drift, glacial meltwater channels as at the Nick O' Pendle, and glacially smoothed and scratched limestone pavements as were to be seen later in the day.

The top of the Bowland Shales are overlain by the Pendle Grit, a sand-rich, submarine slope complex of channels and fans. At the Nick O' Pendle, the Pendle Grit is thought to have formed at the distal end of a delta as a product of deposition from turbidites. Paul Kabrna explained how the Pendle Grit is a good reservoir rock and has been used by the hydrocarbon companies for training students in oil exploration. The Bowland shales are potentially ideal source rocks for oil, so the overlying Pendle Grit is well placed for migration and storage of hydrocarbons in the sandstone.

The Pendle Grit at the Nick O' Pendle is a medium grained arkosic sandstone, exposed in three small quarries. The massive sandstone bodies are commonly scoured or fluted, particularly at the base of beds. Undulose bedding planes have many shale clasts that may define amalagamation surfaces. Discrete shale clast breccias at the base of beds may indicate the presence of debrites, one of which was seen in the central quarry. Analysis of these debrites can indicate the density of the turbidite. The group then crossed the road and looked at Pendle Grit beds in a small disused quarry with wavy channel bedding and some good load casts exposed on the underneath of one bed.

After driving to the car park of the Calf's Head, Worston, the group walked to two exposures in the A59 road cuttings just east of Clitheroe. The Crow Hill Waulsortian mud mound was built by bacteria forming and then holding together the lime mud that became the micritic limestone seen in the first exposure. Waulsortian mud mounds are not found elsewhere in the geological column, and this led to speculation

Figure 3. Bellman Park Quarry, showing core beds of a Waulsortian mud mound on the left, flank beds to the right and Pendle Hill in the background.

Figure 4. *Calyx of crinoid,* Amphoracrinus gilbertsoni*, found in Bellman Park Quarry.*

whether the type of bacteria had become extinct after the Lower Carboniferous, leaving no organism able to form the mud mounds. It was also considered why the Waulsortian mud mounds should all be arranged in a line in the Clitheroe area; one possibility is that they formed over a line of methane seeps that helped the bacteria to form on the sea bed.

The group then went to the Peach Quarry Limestone, also in the A59 road cutting. Unlike the Crow Hill limestone that is massive, unbedded, micrite with few fossils, the Peach Quarry Limestone consists of thick, well-bedded limestones and thin shale beds with abundant crinoid ossicles. This is a lenticular bed, only found on the eastern side of the Clitheroe anticline, and is thought to have been storm-generated. It represents a period of basin shallowing that took place prior to deposition of the Salthill mudmounds.

After lunch, the group followed the Salthill Quarry geology trail using the Geologists' Association field guide (Bowden, 1997). After the 'bank beds' at the core of the hill at Salthill were formed, in Tournaisian times, a period of fragmentation and erosion of the mound left an unconformity, over which inter-bank, flank and biosparite limestones were draped. At trail points 2 and 9, two small mud mounds are seen, and these are thought to be the start of a third phase of limestone mud mounds in the area (the first phase is at Coplow Quarry, and the second is the line from the Castle through Salthill to Twiston. Geopetals (fossil spirit-levels) in the hollows of crinoid stems, seen at point 3, have been used to determine that the flank beds had been laid down horizontally prior to Variscan tectonis that left their present dip of about 25º south. Farther round the trail, point 6 has a great diversity of crinoids that have been collected in the past. A stone seat has been made of large slabs of crinoid-rich limestone, set with some tiles depicting crinoids (Fig. 1). Glacially smoothed limestone slabs lie at point 8.

The group then crossed the road into Bellman Park Quarry (Fig. 3), another in a Waulsortian mud mound, and were met by Simon Moorhouse, the Operations Manager for Castle Cement. At the first outcrop of what appeared to be crinoid-rich flank beds members found two crinoid calyces identified as *Amphoracrinus gilbertsoni* (Phillips) and *Gilbertsocrinus* sp. (Fig. 4). Behind the northern face of the quarry, another excellent area of glacially smoothed and striated limestone had only recently been discovered by Castle Cement. A locally rare goniatite was found in a large loose block. Practically unstratified bank beds in the northern faces of the quarry consist of grey-blue micritic limestone. Folding could be seen in the western face, and a Productoid brachiopod was found in another large loose block.

After returning to the cars, most called it a day, but two members went on to Angram Green where the largest Waulsortian mud mound forms Worsaw Hill and the ridge on the side of Pendle Hill formed by the harder Pendleside Limestone could be viewed. Salthill Quarry, Bellman Park Quarry and the A59 cutting at Crow Hill are all Sites of Special Scientific Interest (SSSIs) and we thank staff at Natural England and Simon Moorhouse, Peter del Strother and others at Heidelberg Cement (Castle Cement) for helping the visit to take place.

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REVIEW

Mineralization in England and Wales by R. E. Bevins, B. Young, J. S. Mason, D. A. C. Manning and R. F. Symes. 2010. Geological Conservation Review Series 36. Joint Nature Conservation Committee: Peterborough, 598 pages, 978-1-876107-566-6, £70, from NHBS, 2 Wills Road, Totnes TQ9 5XN.

This massive volume is the culmination of over 20 years gathering data on Geological Conservation Review (GCR) sites (mostly Scheduled Sites of Scientific Importance: SSSIs) concerned with the varied evidence of the mineralization processes in England and Wales. A companion volume on Scotland has been promised. This Mineralization volume was started by L. Haynes, and I have memories of him interviewing me about Peak District sites, but he then dropped out of the project. The GCR scheme is closing in the summer of 2011 when the series should contain 45 volumes.

This volume summarizes the reasoning behind the selection of 137 sites. After an introductory chapter by R. E. Bevins, the sites are covered in six regional chapters by different authors: Lake District, North Pennines, South Pennines (including Cheshire, Lancashire and Shropshire, but not Staffordshire), Wales, Mendips and Southwest England. The introductory chapter includes tabulations of the types of mineralization and of the special features shown by the 137 sites, together with a history of the mineralization processes through geological time. One aspect of the latter caught my eye: much of the vein mineralization hosted in the Lower Palaeozoic rocks of Wales and the Lake District is now regarded as of Carboniferous age – implying a former cover of Carboniferous strata on top of the older rocks? Each of the GCR sites is covered in about four pages, with an introduction, description, interpretation and conclusion, which tend to some duplication of comments.

As space precludes coverage of all the areas, my remarks are confined to the South Pennines and adjacent areas in Chapter 4 compiled by D. A. C. Manning and others. Three of the local sites are Leicestershire quarries that ceased production long ago and are now partly or completely filled with rubbish; Enderby Warren Quarry was filled in years ago and is now covered by an industrial estate. So what is the point of including them as GCR sites? Calton Hill quarry, east of Buxton, was also largely filled in with rubbish, but a little of its unique basalt with its ultrabasic olivine-rich inclusions is still visible; few traces of its later quartz-hematite veins can be seen. Of the rest of the Peak District sites, those of Treak Cliff with its Blue John fluorspar deposits, Windy Knoll with its bitumens, and Dirtlow Rake with complex multiphase mineral deposition are obviously of national if not international importance; however, parts of Dirtlow Rake have recently been back-filled and levelled. The complex of veins, pipes and replacements in the Masson Mines at Matlock is again a significant aspect of mineralization. I was a little surprised to see Bage Mine near Wirksworth listed – it is the type locality of the lead chloride minerals matlockite and phosgenite (= cromfordite), but recent explorations have failed to find the original site within the accessible workings.

Doubtless, readers with a good knowledge of the Peak District will be able to suggest sites which are not listed; perhaps Magpie Mine's Blende Vein with its unusual sphalerite-calcite pipe veins, and Golconda Mine with its extensive baryte-galena deposits containing uncommon secondary minerals such as hemimorphite and aurichalcite. The unique stalactitic baryte deposit near Arborlow stone circle is not mentioned. The Ecton copper mines of Staffordshire are included, but surprisingly are listed as being in Derbyshire, which explains the absence of Staffordshire from the chapter title! The chapter also includes the Alderley Edge copper deposits in Cheshire, with an account brought up to date by Geoff Warrington. Gipsy Lane brickpit in Leicester, with its unusual vanadium and uranium minerals in the Triassic mudstones hosting gypsum beds, is included, though part of the pit has been filled in and much of the rest is very overgrown. Snailbeach and Huglith Mines are the only sites in Shropshire to be listed, though there were many more mineral deposits and mines.

The entries are accompanied by black and white photographs but their reproduction can be so poor and muddy that it is difficult to make out what they depict. The colour photo on the cover does not appear to be identified inside. The volume concludes with a combined bibliography of 44 pages, though very few are dated later than 2000 and most much earlier - evidence of the long preparation time?

This listing of sites with evidence of mineralization processes is an important contribution to the record of our inheritance. It accompanies others in the GCR series on the Carboniferous Limestone, Karst and Caves, Quaternary, and many other facets of geology, and should be available to all those concerned with planning and conservation, though whether they will have any influence on preservation or control of development is something we shall have to see in the future.

Trevor Ford

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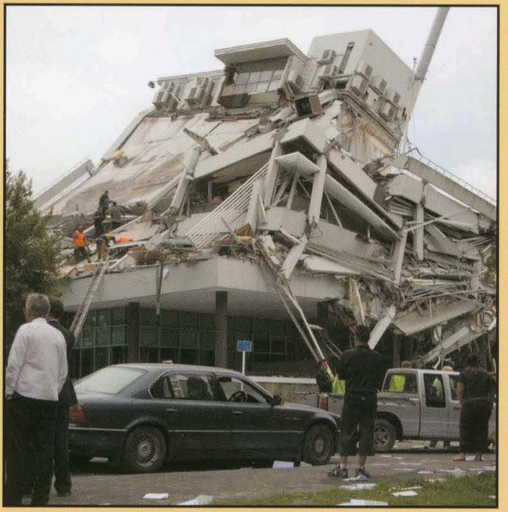
A cumulative index for the ***Mercian Geologist*** is available on the Society website (www.emgs.org.uk). This will have entries added for future volumes, and will also be backdated as far as Volume 13, but these are currently being generated and await completion.



After the earthquake, Christchurch, New Zealand, 2011 (page 283)