MERCIAN *Geologist*

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Front cover: A newly cleared exposure alongside the railway at Colwick Woods, near Nottingham, with inter-bedded red shales and siltstones of the Gunthorpe Formation, part of the Triassic Mercia Mudstone Group. The well-developed thin bedding reflects deposition from flash floods flowing into temporary lakes in a semi-arid alluvial basin, perhaps like parts of the Lake Eyre Basin in modern Australia.

Back cover: (*clockwise from top*) Chrome Hill reefs, Upper Dovedale; Ladybower Reservoir from Bamford Edge; Reynard's Cave, Dovedale; Winnats Pass, Castleton; Lud's Church landslip fissure, Dane Valley. All cover photos by Tony Waltham.

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PROFILE

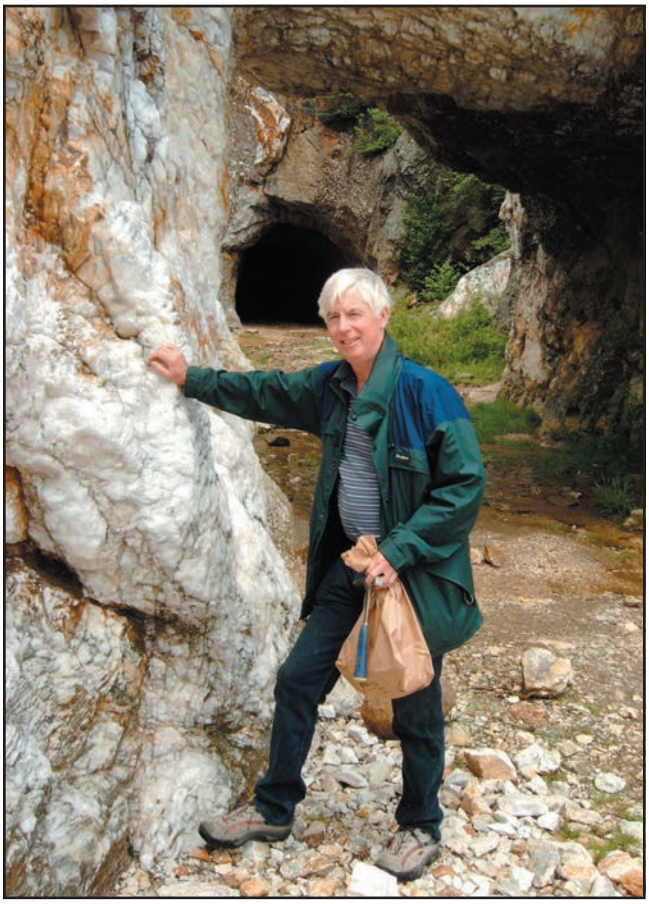
Tim Colman

Our new president was born in a vicarage near Cockermouth, Cumberland, but moved south at an early age to Bedfordshire and Buckinghamshire and then Norfolk. His only scientific ancestor was an uncle who was head of the Marine Biological Station at Port Erin on the Isle of Man. He remembers his parson father taking him to the Hensbarrow china clay pit and South Crofty tin mine in Cornwall, and still has a photo showing him operating a hydraulic monitor at the bottom of the Hensbarrow pit at the age of 12.

He graduated in geology from the University of Durham in 1969. The excitement of the 'nickel boom' and the prospect of travel led him to a graduate trainee position with Consolidated Gold Fields Australia, with a first placement at the Mount Lyell copper mine in Tasmania, where he gained an introduction to open pit and underground mining and ore reserve calculation. After four months he moved on to his next placement, the CGFA exploration division based in Kalgoorlie in Western Australia, arriving as the Poseidon nickel share boom was at its height. Within a couple of days he was 100 km out in the bush, with a student as a field assistant, mapping Archaean volcanic rocks – a far cry from his BSc mapping area of Ashover. The temporary placement was soon made permanent, and he spent the next three years based in Kalgoorlie but mainly living out of a Landrover and caravan on a variety of projects including prospecting for nickel in many areas of the Yilgarn, mapping iron ore in the Hamersleys, drilling heavy mineral sands north of Perth and investigating a copper-zinc prospect in the Pilbara.

He returned to Britain in 1972 to take an MSC in Mineral Exploration and Mining Geology at Leicester University, and was then offered a post as exploration geologist for Irish Base Metals based in Loughrea, County Galway. He spent a year prospecting for lead and zinc, around the Tynagh mine and in County Clare, before returning to Britain in 1975 to take a PGCE at Keele University. He then initiated a geology A-Level course at Forest Fields 6th Form College in Nottingham, where he used his Durham introductory field week as a basis for the A-Level field trip.

After four years of teaching, the call of the minerals was still strong, and he became an Economic Geologist in the minerals division at the Institute of Geological Sciences, which had recently moved from London to Keyworth His first couple of years involved helping to administer a mineral incentive scheme to promote commercial mineral exploration in Britain. This introduced him to many mining company projects, from Islay to Cornwall. From then on, until his retirement in 2007, he was involved in a wide variety of mineral-related projects including mineral exploration, mineral deposit studies, mineral statistics, metallogenesis, radon investigations, GIS developments and several short overseas projects. The latter took him to Zambia, Angola, Turkmenistan, Portugal and the Falkland Islands, before leading a three year project to develop a mineral information system and digital documentation centre in the National Directorate of Geology in Mozambique. His main interests throughout his BGS career remained metalliferous mineral deposits, especially volcanogenic and Mississippi Valley Type ores and their worldwide exploration and development.



He was responsible for the production of two volumes of the BGS publication 'Exploration for metallic and related minerals in Britain: a guide' as well as several Mineral Reconnaissance Programme reports on projects in Aberdeenshire, Anglesey, Southwest Wales and Staffordshire. He investigated the small mineral deposits associated with the Ordovician Snowdon volcanic caldera and contributed to the final seminal BGS memoir on this classic area.

He initiated the now almost annual BGS attendance at the Prospectors and Developers Association of Canada March meeting in Toronto, and helped to foster links with various mining companies. He retains an interest in Irish mineralisation and is still a member of the Irish Association for Economic Geology. He is also a member of the Institute of Materials, Minerals and Mining (IOM3) and was on the committee of the former Nottinghamshire Branch, with a term as President.

Following his retirement from the BGS in 2007, he has become a tutor at the Ecton Hills Field Studies Association mine and has joined their committee.

FROM THE ARCHIVES

An archive photograph of East Midlands geology from the British Geological Survey collection

Fire, ice, flood and earthquake – One Barrow Quarry, Blackbrook Reservoir

This image was taken in 1904, and is one of a series commissioned by the Leicester Literary and Philosophical Society, that records the rock exposures and quarries created during construction of the dam, viaduct and earthworks for the Blackbrook Reservoir, near Shepshed, Leicestershire.

It shows One Barrow Quarry, which, together with other quarries nearby, preserves a series of volcaniclastic tuffs and breccias within the Blackbrook Group of the Charnian Supergroup. The volcanism was associated with a Neoproterozoic island arc complex, and the South Quarry Breccia Member exposed here is of particular interest, as it may represent a major debris flow deposit that ran down the submarine slopes of the volcanic pile, perhaps triggered by liquefaction associated with a seismic event.

By an uncanny coincidence, debris flows, gravity and seismicity have also played their part in the chequered history of Blackbrook Reservoir itself. The story of the reservoir is linked inextricably with the ill-fated Charnwood Canal. This was built in the late 18th century, at a time when 'canal mania' is often said to have gripped the nation. The canal's purpose was to carry coal from mines at Coleorton, near Ashby, to the Soar Navigation at Loughborough, avoiding tortuous transport by handcart or packhorse. After much vacillation in Parliament about the canal's feasibility and usefulness, the engineer Christopher Staveley was engaged in 1791 to survey and design the canal. His design involved a combined contour canal and tramway system, the latter to avoid the construction of locks to cope with the steep gradients at each end of the route. Completed in 1794, the canal was immediately plagued with a lack of water, so the first Blackbrook Reservoir was hurriedly constructed by 1796 to solve the problem. The reservoir's earth dam initially appeared substantial, until a rapid thaw at the end of a long, harsh winter in February 1799 brought the dam to bursting point. Despite a few days of valiant efforts to repair the cracks, the dam eventually failed like 'a clap of thunder', sending workmen running for their lives. The reservoir emptied in just 11 minutes, unleashing a torrent of water and debris that drowned hundreds of sheep, washed away farm buildings and crops, and inundated large parts of downstream Shepshed and Loughborough. Although the dam was re-built and the canal re-commissioned in 1801, it was too late to save the mines at Coleorton and Thringstone, which soon went out of business. So, by 1804, the reservoir was drained and the dam was subsequently dismantled.

The present Blackbrook Reservoir was completed in 1906, but history was nearly repeated in February 1957 when the dam was damaged by a magnitude 5.3 earthquake that shook the East Midlands area. Large coping stones were moved and cracks appeared in the dam face, but this time the dam was fortunately made of tougher stuff, and subsequent inspection proved the structure to be sound.

One Barrow Quarry provided a source of stone for construction of the dam and associated masonry, and is now recognised as a Site of Special Scientific Interest on account of its geological importance.

Andy Howard, British Geological Survey

One Barrow Quarry, near Blackbrook reservoir, photographed in 1904 (Image BAAS03791 from the geological photograph collection of the British Association for the Advancement of Science, archived at the British Geological Survey Library, Keyworth, Nottingham).

If any reader can recognise the make and model of the vintage car in the foreground, please let the editor know.

GEOBROWSER

Charles Darwin and geology

This year marks the bicentenary of Darwin's birth and 150th anniversary of his volume: On the Origin of Species by Means of Natural Selection, which established him as the founding father of modern evolutionary biology. Rather less is known of Darwin the geologist, even though during the Beagle voyage he devoted 1383 pages of notes to geology, and only 368 pages to the wildlife he found. His comprehensive observations included the weathering of rocks; igneous processes and metamorphism; volcanic and seismic activity; uplift of mountain ranges, and the development of oceanic islands and their coral reefs through time (*Geol. Assoc. Rockwatch Magazine, 50, p.32*).

Some indication of Darwin's polymath character is revealed by his rather chequered college career (*The Autobiography of Charles Darwin by Nora Barlow, 1958*). At first he followed his father's example by studying medicine, at Edinburgh University. There he became acquainted with 'several young men fond of natural science' and he also attended lectures on geology; although he deemed those 'incredibly dull'. Leaving Edinburgh before completing his medical degree he went on to Cambridge, but confessed to 'wasting' three years there, even though he did gain a degree in Theology, Euclid and the Classics. His real interest evidently lay in natural sciences, for he attended lectures on botany and enjoyed collecting and describing beetles. Through these activities he met J. S. Henslow, who organised informal discussions covering natural science topics that included geology. It was Henslow who introduced the newly-graduated Darwin to Professor Adam Sedgewick, whom he accompanied to Wales in the summer of 1831. This rather brief field course did not satisfy Darwin's curiosity about geology and landscapes, but it enabled him to acquire many basic geological skills, which he subsequently augmented by avid perusal of Lyell's Principles of Geology.

Darwin's somewhat informal geological training was to prove vital for the Beagle voyage of 1831-36, during which he noted that 'The investigation of the geology of all the places visited was far more important… by recording the stratification and nature of the rocks and fossils at many points, always reasoning and predicting what will be found elsewhere, light soon begins to dawn on the district, and the structure of the whole becomes more or less intelligible'. This might well sum up the analytical approach used by Darwin as he formulated his theory of evolution.

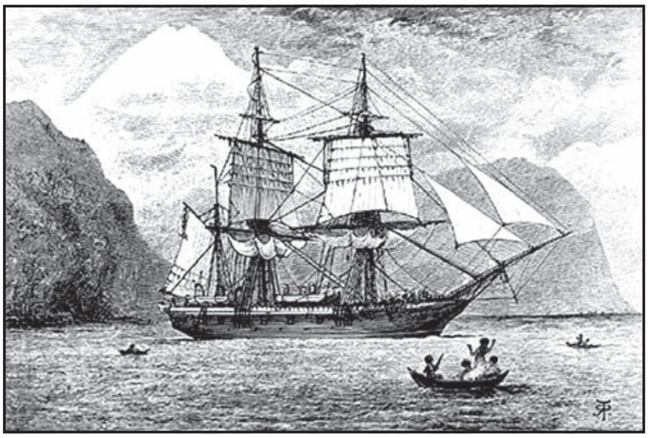
Darwin's tree of life

Although much has been made of Darwin's concept of natural selection, his theory of evolution between species had an equally important theme. He compared this to a 'great tree', and it was an elegant depiction of how different species might be related through biological evolution and diversification. Natural selection furnishes the explanation for the Tree, which as Darwin noted provided the 'propinquity of descent' lacking from Carl Linnaeus's hierarchical system for grouping organisms. The Tree of Life has been described as the unifying principle for understanding evolutionary history (*New Scientist, 2009, p.34*). Its base has come to be represented by the LUCA (Last Universal Common Ancestor) and out of this grows the trunk, which bifurcates outwards into branches, some of which continue upwards to end at currently extant species and others, lower down, completed by species now extinct. This tree is typically portrayed in simplified form by modern 'artist-scientists', even though Darwin's most commonly replicated sketch is not particularly tree-like. Moreover, Darwin experimented with ten other tree-variants, indicating an awareness of the complexities of evolution.

For some 150 years biologists have been filling in the various branches of this idealized tree, but since the mid-1960's our perception of evolution has been profoundly modified and greatly improved by the science of molecular phylogenetics, which attempts to determine the rates and patterns of change occurring in DNA and proteins and to reconstruct the evolutionary history of genes and organisms. This new way of thinking followed from the discovery of DNA in 1953, but was given tremendous impetus by the bio-technological advances of the 1990's that enabled the molecular analysis of DNA and RNA protein sequences.

Challenges to Darwin's concepts

At first it was hoped that the new techniques would confirm the tree of life scenario, and fill in more of the gaps. However, they very soon led to the discovery of the archaea (*Proc. National Academy of Science, USA, 1977, p.5088*). These unicellular organisms were previously thought to be bacteria, but are now regarded as an entirely new Third Domain of life, separate from bacteria and eukaryotes (which include animals). Their traces occur in rocks as old as 3.8 billion years, when the planet was hostile to life, and today they include the 'extremophile' organisms, which can exist in very hot, very cold, acidic or anaerobic environments. Importantly, they possess some advanced processes connected with gene transcription and translation, and in evolutionary terms may have an ancestral link

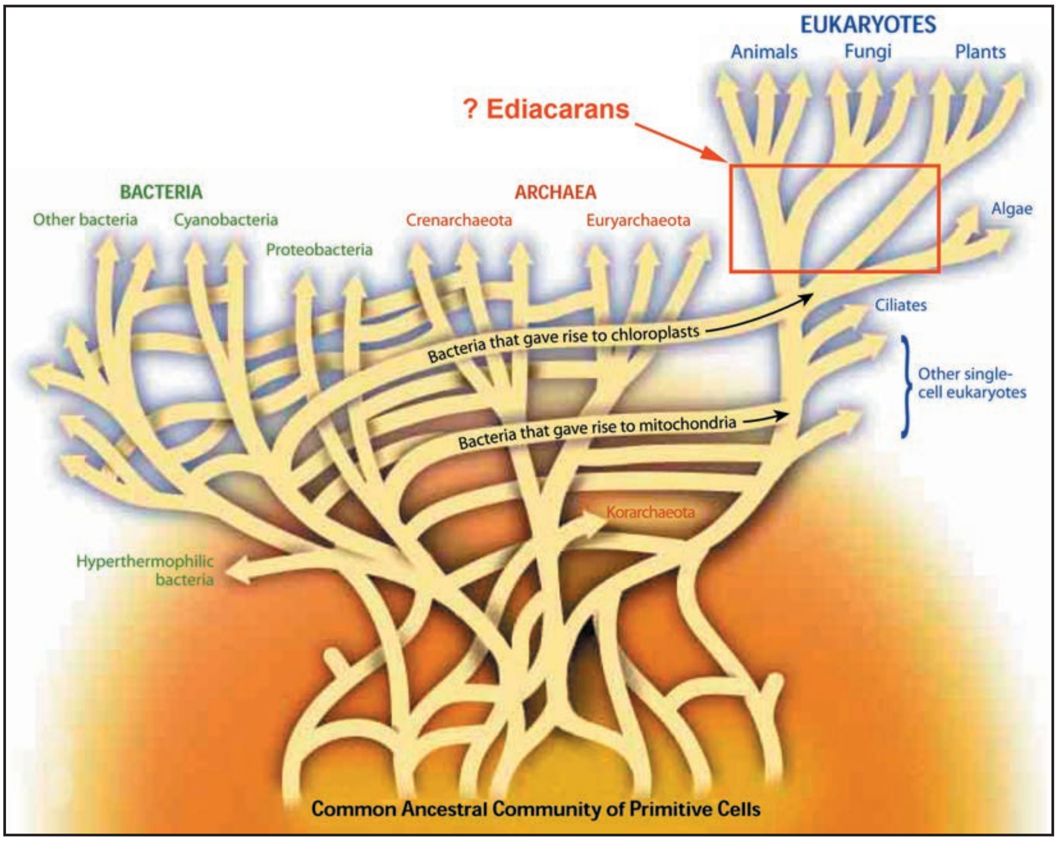


W Ford Doolittle's drawing of the Revised Tree of Life, *to which we have added the possible evolutionary situation at c. 580-542 Ma, when Ediacarans proliferated.*

A chloroplast is the part of a cell that conducts photosynthesis.

A mitochondrion is the part of a cell involved with controlling cell growth and cell functions but with DNA similar to bacterial genomes.

Below left: HMS Beagle



to eukaryotic organisms (*Proc. National Academy of Sciences, USA, Vol. 87, 1990*). Furthermore, the new DNA sequencing databases show that certain bacterial genes also form vital parts of eukaryotic cells, as well as being present in archaea. To paraphrase W. Ford Doolittle (*Scientific American, February 2000, p.90*), this suggests that the pattern of evolution is not as linear or treelike as Darwin imagined it, and although genes do show vertical descent from generation to generation, there is a further process at work, called horizontal gene transfer (HGT). This is facilitated by viruses or 'bacterial conjugation' and must have profoundly affected at least the early course of evolution. There is increasing acceptance that way back in time, all animal life originated through fusion between bacteria and archaea, and HGT is implicated in various evolutionary 'jumps' towards viable, multicellular organisms.

Doolittle's new version of evolution retains the traditional or 'consensus' treelike branching mode at the top for multicellular animals, plants and fungi where both gene transfer and Darwinian natural selection could work. Lower down, however, there is a mesh-like series of linkages, sometimes called a 'web', to symbolize rampant horizontal gene transfer between unicellular organisms. This modified 'tree' also lacks a Universal Common Ancestor, and suggests that the three major domains of life probably originated from a population of primitive cells with different combinations of genes.

Should Darwin's tree be uprooted?

Most scientists agree that Darwin's theory of descent remains valid, and that despite Doolittle's modifications the tree metaphor is still an apt, albeit oversimplified depiction of early evolution. This year, however, a controversy focussed on the biomolecular discoveries of the previous decade has entered the popular media, with attention-grapping headlines such as: 'Darwin was Wrong' (*New Scientist, January 24, 2009*) and 'Darwin was wrong and misleading' (*The Telegraph, January 22, 2009*). These attacks have been repudiated by evolutionary scientists, who maintain that they not only misrepresent the outcomes of biomolecular studies, but also inspire creationists to mislead people into believing that the theory of evolution by common descent is wrong. A succinct riposte to such articles can be found online (*S. Schafersman; February, 2009 'The Death of the Tree of Life has been greatly exaggerated'*). It features a letter to the New Scientist from a panel of experts, including Richard Dawkins, insisting that the tree of life concept is not fundamentally unsound, but it is '…more complicated than was realised before the advent of molecular genetics. It is still true that all of life arose from "a few forms or... one", as Darwin concluded in The Origin of Species. It is still true that it diversified by descent with modification via natural selection and other factors'.

Does this help understand Charnian fossils?

The apparent absence of fossils in Precambrian rocks bothered Darwin, although in Origin of Species he presciently wrote that: 'Traces of life have been detected in the Longmynd beds beneath Barrande's so-called primordial [Cambrian] zone.' He might also have mentioned the organic impressions discovered in Charnwood Forest in 1848 (*Geobrowser, 2008*), had he known about them. We now appreciate the true richness and diversity of the Ediacaran biota, with 325 Precambrian fossils featured in the glossary of The Rise of Animals (*reviewed in Mercian, 2008, p.67*). Few of these actually survived beyond the Precambrian-Cambrian boundary (542 Ma), so the biological affinities of those that did not can only be guessed at. Doolittle's modified Tree of Life helps here, since it places Ediacarans at a very early stage in multicellular organisation, when processes such as horizontal gene transfer, hybridisation and symbiosis were considerably more fluid. The referral of the more enigmatic Ediacarans to 'failed experiments in life' rings true, though it may be more accurate to say that those particular 'experiments' produced unexpected and bizarre organisms. Suited to environmental niches that existed then, they were unable to evolve further or to compete with the more genetically robust species that went on to become the true ancestors of modern life.

THE RECORD

We welcome new members who have joined the Society during 2008. Our membership now stands at 343 with an additional 40 institutional members.

Indoor Meetings

Many of the indoor meetings this year seem to have had historical as well as geological interest. They began with the members' evening which, under the chairmanship of Gerry Slavin, was held after the AGM in March. The subjects of this series of short talks were Iceland, Faroe Islands and zeolites (Alan Dawn), Ardnamurchan (Robert Gill), The rise of the roddens (Dinah Smith) and Water wheels and geology in the Derwent Gorge, Matlock (Lynn Willies)

Also in March, there was a joint meeting with the Yorkshire Geological Society at Keyworth entitled The Erosion of Northern Britain.

April's lecture was about the Midland Influences on William Smith, given by Peter Banham.

The winter programme began in style October with Geology of the Languedoc, presented by Roger Suthren, complete with wine tasting.

In November, Will Watts spoke about the Rotunda Museum in Scarborough, its role in the beginnings of geology and its recent redevelopment.

December's speaker was Tony Waltham, who gave us the Salt Terrains of Iran, and this was followed by the Christmas buffet.

In January, the Secret of Sherwood Forest was disclosed by Kevin Topham from Dukes Wood Oil Museum.

The Foundation Lecture this year was on Palaeobotany of Antarctica and was given by Professor Jane Francis.

We are grateful to Richard Hamblin for organizing this year's successful programme of speakers, and to Gerry Shaw for organizing the refreshments.

Field Meetings

Once again a varied programme of field excursions was organised by Ian Sutton to whom we give our thanks. Also due thanks to the field trip leaders who share with us their time and their knowledge.

In May, Paul Guion led a trip concerning hydrocarbon reservoirs and the Dukes Wood oil museum.

Evenings in June were to Charnwood Forest with John Carney, and to Middleton Moor for the Hopton Wood Stone led by Ian Thomas.

July saw a whole day visit to the Millstone Grit of Skipton Moor led by Neil Aitkenhead, and also an evening walk to look at the gravels and tills in Charnwood Forest with Keith Ambrose.

The weekend excursion led by Ian Sutton was this year to The Gower in South Wales, for its fossils and its fine structural geology.

Council

Council met formally on six occasions during the year.

As no Treasurer had been elected at the Annual General Meeting, Colin Bagshaw was co-opted to the position in May. Paul Guion and Ian Sutton were also co-opted to Council on the same occasion.

This has been a quieter year for projects. We have given our support to the Ecton Hill Field Study Centre, and have donated £100 to Dukes Wood Oil Museum towards the cost of replacing their stolen notice boards. The Hemlock Stone is currently being researched, and the back copies of the Mercian Geologist are being converted into electronic form both for archive purposes and to make the contents more widely available. The Society continues to support Geodiversity in the East Midlands, with some of our members helping to update the RIGS databases.

Thanks are due to Sue Miles for editing the Society's Circular (which now goes to half the membership via e-mail), to Tony Waltham for editing the Mercian Geologist (including The Geology of Chatsworth which was off-printed to form a special publication), and to Rob Townsend for continuing to maintain the Society's website.

To conclude I would like to thank all those I have not specifically named in my report who work hard to further the aims of the Society.

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 and non-members.

The Geological Evolution of Warwickshire

Jonathan D. Radley

Abstract: The geology of the central English county of Warwickshire demonstrates 600 million years of continental drift, tectonism and palaeoenvironmental change. Neoproterozoic and Lower Palaeozoic rocks demonstrate island arc accretion, Cambrian marine transgression, and Ordovician subduction-related intrusive igneous activity. Times from Upper Palaeozoic to Triassic witnessed mainly continental environments at equatorial and circum-equatorial latitudes, including deposition of coal measures and red-beds. Latest Triassic marine transgression ultimately led to deposition of richly fossiliferous Jurassic sediments. The solid geological succession and its structure indicate several episodes of folding, faulting and erosion, influenced by deep-seated structural lineaments within the central English Precambrian basement. The modern landscape is influenced by these ancient structures and reflects Palaeogene and Neogene uplift and erosion, as well as further changes by Quaternary erosion and weathering, and glacial and fluvial deposition.

Warwickshire demonstrates remarkable geodiversity, with a mainly sedimentary succession representing roughly 600 million years of Earth history. The county is characterised by a mainly agricultural landscape of low, rolling hills and vales. Covering an area of just under 2000 sq km, Warwickshire tells a story of continental drift across the face of the globe, tectonism, climate change, biological extinctions and sweeping evolutionary changes among the region's plant and animal inhabitants. Many aspects of Warwickshire's geology are of national and international importance and have attracted the attention of researchers and collectors since the earliest days of geological investigation in Great Britain. Locally collected palaeontological specimens can be found in many local, regional and national museums and other collections. Highlights include the Cambrian faunas of the Nuneaton Inlier (Illing, 1916; Rushton, 1966; Taylor & Rushton, 1971; Brasier, 1984), Permian-Triassic, continental-freshwater, vertebrate faunas and trace fossil assemblages of the Warwick-Kenilworth district (Walker, 1969; Paton, 1974, 1975; Benton & Spencer, 1995; Tresise & Serjeant, 1997), spectacular Early Jurassic marine reptiles from southern and eastern Warwickshire (Cruickshank, 1994; Benton & Spencer, 1995; Smith & Radley, 2007), and the Middle Pleistocene fluvial-glacial succession of eastern Warwickshire with its fossiliferous channel deposits and Lower Palaeolithic stone tools (Shotton, 1953; Shotton *et al*., 1993; Keen *et al*., 2006). The county's geological history was summarised most recently by Shotton (1990). Since then, new data and interpretations have been provided principally by the British Geological Survey (BGS), through a series of revised geological maps and associated sheet memoirs.

Warwickshire sits across the outcrop of generally shallow-dipping Triassic and Jurassic strata that reaches from Devon to the Yorkshire coast (Fig. 1). Constituting the county's backbone, the Warwickshire Coalfield diversifies this pattern, forming an elevated area between the Triassic lowlands of the Hinckley and Knowle basins in the east and west respectively (Bridge *et al*., 1998). Geologically, the coalfield and adjacent Nuneaton Inlier equate to the Coventry Horst, bounded partly by the Polesworth Fault in the northeast and by the Western Boundary Fault (Fig. 2). These faults and a number of other local structures appear to be underpinned by deep-seated lineaments within the largely concealed Precambrian basement of the Midlands Microcraton (Lee *et al*., 1990). In

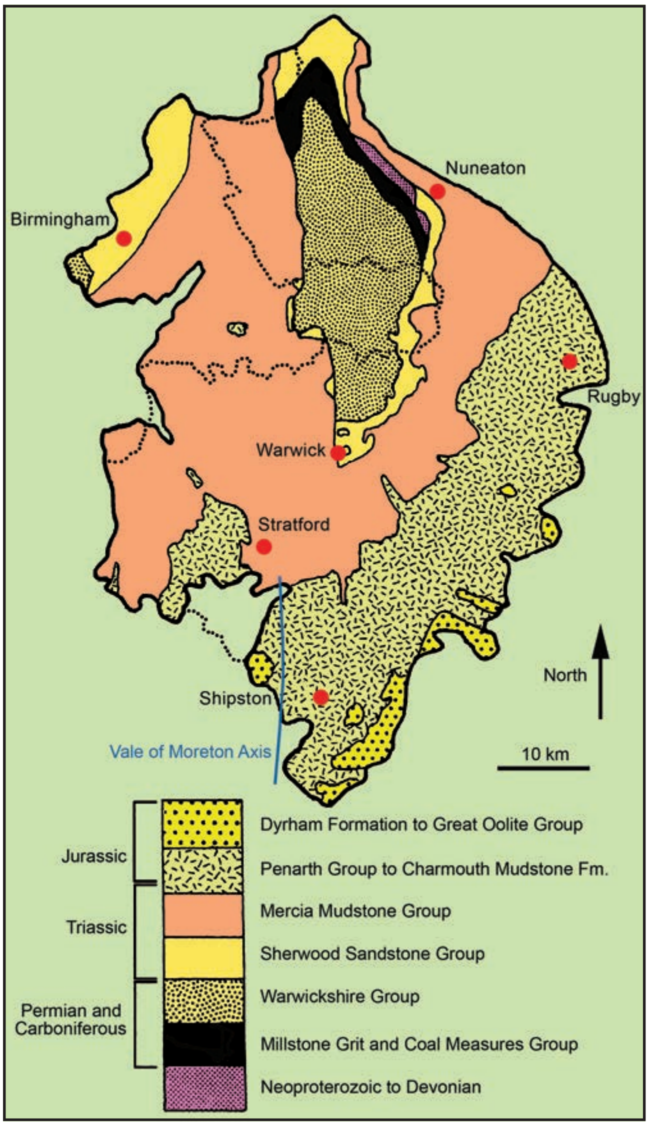


***Figure 1**. Outline solid geology of Warwickshire at its earlier extent; the new county boundary is shown by the dotted line.*

recent decades, surface and subsurface investigations, carried out principally by the BGS, have underlined the important role of such structures in regional tectonic evolution (Carney, 2007). The Western Boundary Fault (Fig. 2) has a typical, north-south 'Malvernoid' trend. This is a widespread structural grain in the West Midlands, possibly inherited from a Neoproterozoic suture zone (Pharaoh *et al*., 1987a; Pharaoh & Carney, 2000). Along the northeastern margin of the Nuneaton Inlier, the NW-SE trend of the Polesworth and Warton faults is of 'Charnoid' aspect, reflecting a proximity to the concealed Caledonides of the eastern Midlands, and also Warwickshire's position near the northern corner of the microcraton (Pharaoh *et al*., 1987b; BGS, 1996; Fig. 3).

The surface geology of the Coventry Horst is dominated by the Upper Carboniferous to Lower Permian Warwickshire Group (Fig. 1), largely comprising non-marine mudstones and sandstones developed partly as red-beds (Powell *et al*. 2000; Waters *et al*., 2007). The Warwickshire Group is flanked around the northern edge of the horst by the underlying Westphalian Coal Measures, traces of Namurian Millstone Grit and Devonian Old Red Sandstone, and steeply-dipping Neoproterozoic and Lower Palaeozoic rocks that have been extensively quarried in the Nuneaton Inlier (Taylor & Rushton, 1971; Bridge *et al*., 1998). Quaternary sands, gravels and clays are widespread throughout the county, including glacial deposits and river terrace gravels (Shotton, 1990).

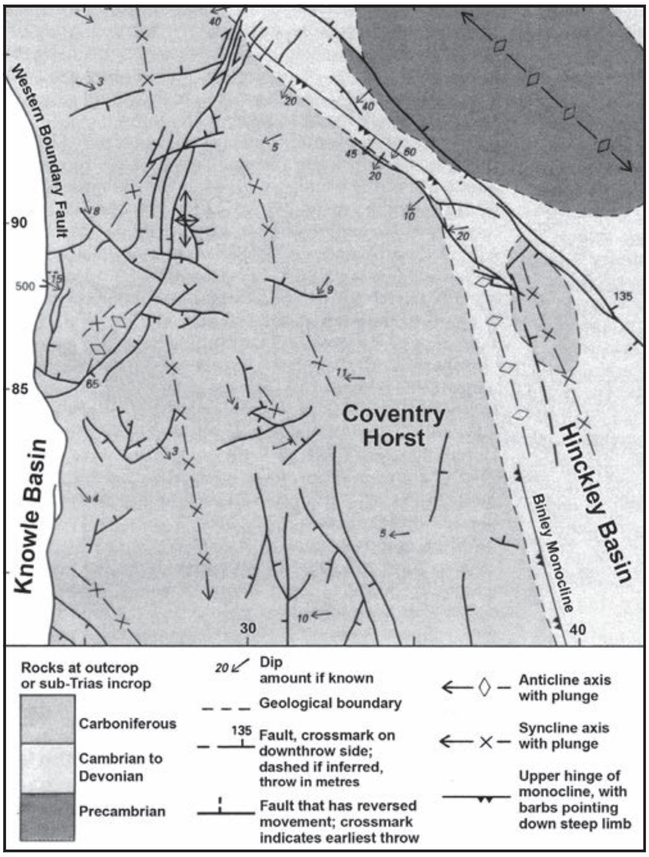


Figure 2*. Geological structure of the Warwickshire Coalfield (after Bridge et al., 1998).*

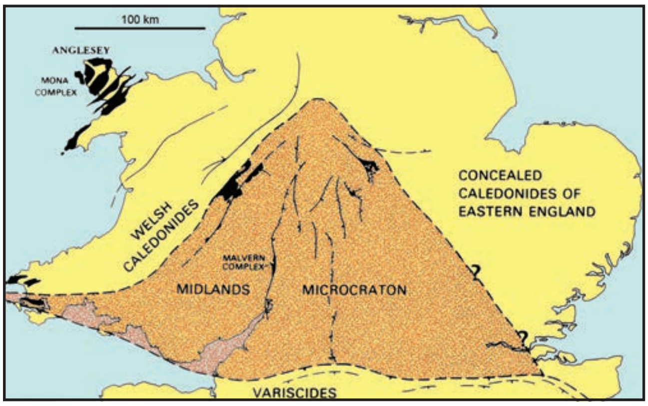


Figure 3*. Outline structural framework for the Midlands Microcraton (after Pharaoh et al., 1987b).*

Neoproterozoic

The geological story commences with the Neoproterozoic (Charnian) Caldecote Volcanic Formation that crops out within the Nuneaton Inlier along the northeastern margin of the Coventry Horst. Judkins' Quarry, north of Nuneaton, has historically provided the most extensive exposure (Fig. 4). A range of volcanic lithologies has been documented (Allen, 1968; Carney & Pharaoh, 1993). Coarser-grained, crystal-rich rocks are probably marine pyroclastic flow deposits derived from dacitic magmas; finer-grained tuffs were deposited subaqueously as ash and dust following andesitic eruptions. Radiometric dates from intrusions within the volcanic pile prove that magmatic activity terminated at about 600 Ma (Tucker & Pharaoh, 1991; Bridge *et al*., 1998). Geochemical studies show that these rocks formed part of the subduction-related Charnian arc along the western margin of the Gondwana continent; a component of the Avalonian arc complex (McIlroy *et al*., 1998; Pharaoh & Carney, 2000). Palaeomagnetism of the Caldecote Volcanic Formation indicate that it formed at a latitude of about 27.5ºS (Vizan *et al*., 2003).

Figure 4*. Northwestern end of Judkins' Quarry, Nuneaton, with tuffs and intrusive volcanic rocks of the Neoproterozoic Caldecote Volcanic Formation, overlain by well-bedded sandstones of the Lower Cambrian Hartshill Sandstone.*

Lower Palaeozoic

Some time prior to the Cambrian but postdating the local magmatic activity, the arc complex (Charnwood Terrane of Pharaoh *et al*., 1987b) had collided with others to form the microcontinent of Avalonia (Carney, 2007). This collage of island arc terranes now constitutes the crust of central England (Lee *et al*., 1990; Bluck *et al*., 1992; British Geological Survey, 1996;). Accordingly, the Lower Cambrian Hartshill Sandstone Formation rests unconformably on the slightly metamorphosed Caldecote Volcanic Formation throughout the Nuneaton Inlier, and indicates marine transgression around 520 Ma (Brasier, 1985; Carney *et al*., 1992; Rushton, 1999). At Judkins' Quarry, sandstones and conglomerates resembling beach and shoreface deposits rest on a fissured surface of volcanic rocks, tentatively interpreted as a wave-cut platform. Nearby, at Boon's Quarry, the oldest Cambrian rocks are relatively poorly-sorted sandstones resembling submarine debris flows, overlying spheroidal-weathered tuff (Bridge *et al*., 1998; Rushton, 1999; Fig. 5). The overlying strata of the Hartshill Sandstone Formation (Fig. 6) are dominated by grey, red and maroon sandstones, some glauconitic, deposited in shoreface to inner shelf environments. Continental reconstructions for the southern British Cambrian indicate a setting far south of the equator (McKerrow *et al*., 1992; Rushton, 1999; Holdsworth *et al*., 2000).

An Early Cambrian trace fossil assemblage dominated by simple trails occurs at several horizons within the Hartshill Sandstone Formation (Brasier & Hewitt, 1979), notably within the Tuttle Hill and Jee's members. The phosphatic and stromatolitic carbonates of the Home Farm Member possibly signify sediment starvation due to sea-level rise (Bridge *et al*., 1998; Rushton, 1999). Significantly they have yielded simple shelly fossils of Tommotian-Atdabanian age allowing comparison with contemporaneous assemblages in Newfoundland and Siberia (Brasier, 1984, 1985, 1992).

Figure 5. *Spheroidally weathered volcanic rocks of the Charnian Caldecote Volcanic Formation overlain unconformably by pebbly sandstones of the Lower Cambrian Hartshill Sandstone Formation in Boon's Quarry, Hartshill.*

Figure 6. *Lower Cambrian Hartshill Sandstone Formation at Midland Quarry, Nuneaton.*

Above the sandstones, the Cambrian and Early Ordovician Stockingford Shale Group was deposited in outer shelf settings following a major marine flooding episode (Bridge *et al*., 1998; Rushton, 1999). Dominant rock-types include dark-coloured blocky to fissile mudstones; some pyritic or bioturbated. Sandstone beds are conspicuous at some levels, for example within the Mancetter Shale and Moor Wood Sandstone formations. Fossils recovered from the Stockingford Shale include sponge spicules, brachiopods and trilobites; the latter proving the presence of many standard English-Welsh Cambrian biozones. At the top of the Stockingford Shale, the Merevale Shale Formation yields the graptolite *Rhabdinopora flabelliforme*, indicating the Lower Ordovician Tremadoc Series (Taylor & Rushton, 1971; Bridge *et al*., 1998). Early nineteenth century workers interpreted the Hartshill Sandstone and Stockingford Shale as Carboniferous, but the Cambrian age was proved in the 1880s by Professor Charles Lapworth of the University of Birmingham, on palaeontological grounds (Lapworth, 1882). Significantly, this work confirmed the great antiquity of the underlying Caldecote volcanic rocks.

The crust beneath southern Britain broke away from Gondwana probably during the Ordovician Period. This crustal fragment (Avalonia) drifted northwards to a latitude of around 20ºS throughout the Ordovician, a process that involved progressive closure of the Iapetus Ocean and opening of the Rheic Ocean (Woodcock, 2000a; Rushton, 1999; Cocks & Torsvik, 2002). Post-Tremadoc Ordovician sedimentary rocks are absent in Warwickshire, though Late Ordovician (early Ashgill) magmatism is seen in the lamprophyre and diorite sills of the Midlands Minor Intrusive Suite, which are widespread in the Nuneaton Inlier (Bridge *et al*., 1998; Carney & Pharaoh, 1999; Fig. 7). The intrusions locally cross-cut folds within the Cambrian-Tremadoc sedimentary succession, indicating an intra-Ordovician

Figure 7. Eastern end of Midland Quarry, Nuneaton, with intrusive rocks of the Midlands Minor Intrusive Suite, flanked by Lower Cambrian Hartshill Sandstone and overlain unconformably by bedded breccias and sandstones assigned to the Triassic Bromsgrove Sandstone Formation.

deformational phase (Bridge *et al*., 1998; Vizan *et al*., 2003; Fig. 8). The intrusions are probably a late-stage product of subduction that took place along the northern Avalonia margin, in the general area of northwest Britain (Bridge *et al*., 1998; Woodcock, 2000a). This accompanied the final stages of closure of the Iapetus Ocean which, by Late Devonian times, led to the joining of Avalonia with Laurentia and Armorica along a suture zone located within the Southern Uplands of Scotland. This resulted in the formation of Laurussia, the Old Red Sandstone Continent (Woodcock, 2000b).

Silurian strata are not seen in Warwickshire, though derived pebbles of Silurian sandstone are locally abundant in Late Carboniferous alluvial beds. This period marked a continuing drift of Eastern Avalonia towards the equator (Torsvik *et al*., 1996; Holdsworth *et al*., 2000). Thirty kilometres west of the Warwickshire coalfield, the Wenlock reefs of Dudley, West Midlands, confirm a climate of subtropical or tropical aspect. It seems likely that an unknown thickness of Lower Palaeozoic strata was eroded from the northern part of the Midlands Microcraton during mild Early to Middle Devonian (Acadian) deformation and uplift (Bridge *et al*., 1998; Woodcock *et al*., 2007).

Upper Palaeozoic

The Late Devonian Oldbury Farm Sandstone Formation of the Merevale area near Mancetter, rests unconformably upon Cambrian mudrocks (Taylor & Rushton, 1971). The Devonian age of the Oldbury Farm Sandstone (Bridge *et al*., 1998) was first confirmed on palaeontological grounds by the BGS during the early 1960s; prior to which it was thought to be Upper Carboniferous in age. The Oldbury Farm Sandstone comprises predominantly alluvial mudstones, sandstones and conglomerates featuring burrowing, mudcracked surfaces and calcrete developments. A marine interval marked by a shelly fauna indicates a late Devonian transgression from the south (Taylor & Rushton, 1971).

Carboniferous times witnessed convergence of the eastern margin of Laurussia with Gondwana, bringing central England northwards to roughly equatorial latitudes (Turner *et al*., 1985; Guion *et al*., 2000). North of the zone of major Variscan deformation, Late Devonian to Lower Carboniferous extension led to the development of an extensional basin (the Pennine Basin) bordered along its southern edge by the Wales–London-Brabant Massif (Cope *et al*., 1992; Guion *et al*., 2000; Fig. 10). In Upper Namurian times, thermal sag within the Pennine Basin (Fig. 8) was accompanied by deltaic progradation from the north, and deposition of sandstones and mudstones (Millstone Grit) unconformably on Cambrian-Ordovician rocks in an embayment along the northern edge of the massif (Taylor & Rushton, 1971; Fulton & Williams, 1988). Later, in Westphalian (Langsettian-Duckmantian) times, this area became the site of Coal Measures deposition, the strata ultimately becoming the Warwickshire Coalfield (Fulton & Williams, 1988; Guion, 1992).

The Pennine Coal Measures Group (Waters *et al*., 2007) thins to the southeast (Fulton & Williams, 1988)

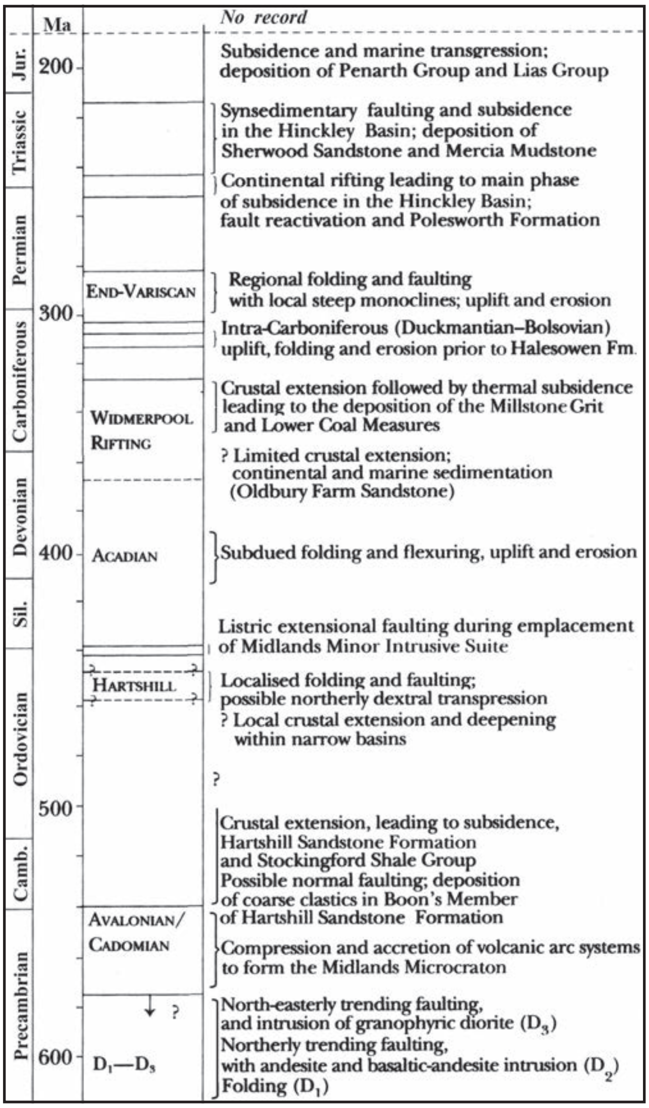


Figure 8. Chronology of main structural events in Warwickshire (after Bridge et al., 1998).

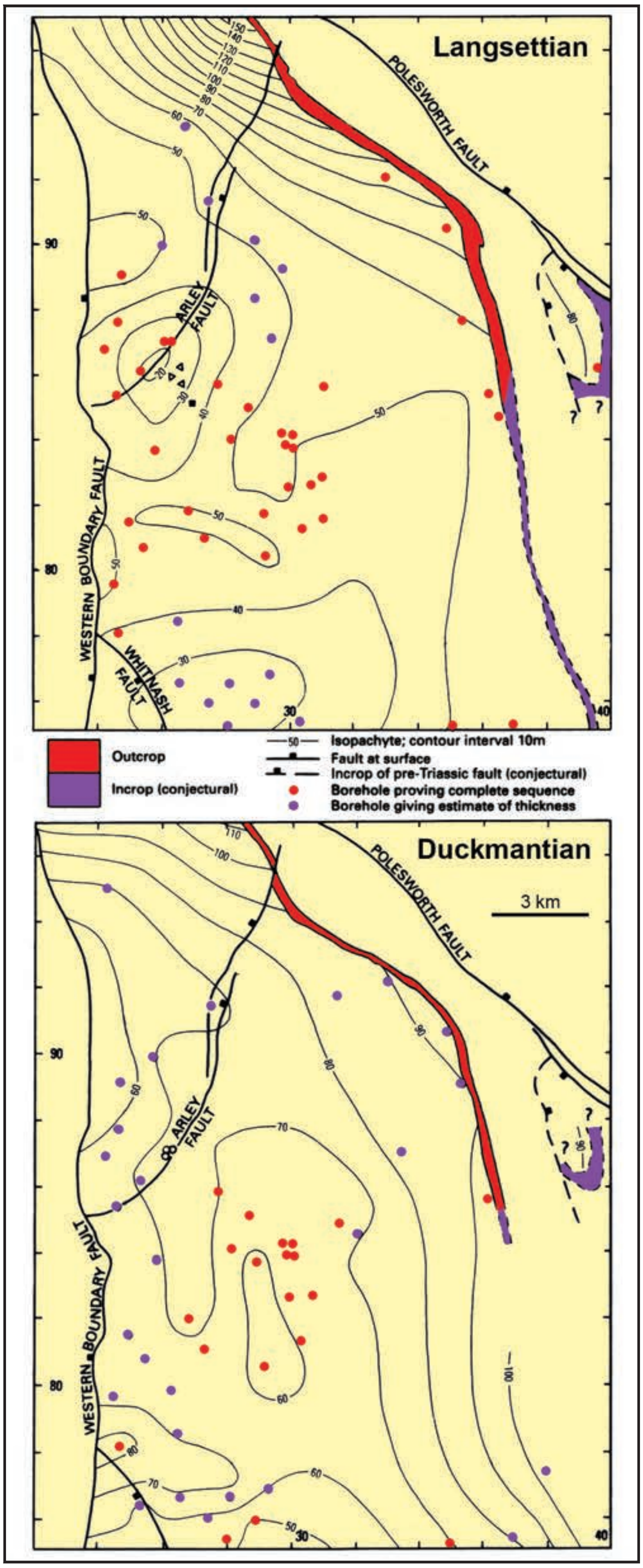


***Figure 9**. Isopach maps of Langsettian and Duckmantian (Westphalian) strata in the central part of the Warwickshire Coalfield (after Bridge et al., 1998).*

and onlaps the Millstone Grit to rest upon Cambrian mudrocks (BGS, 1994). Facies and thickness variations within coal seams, marine bands and sand bodies close to the Western Boundary Fault (Fig. 9), indicate that this structure was active in Upper Carboniferous times (Fulton & Williams, 1988; Bridge *et al*., 1998).

The Coal Measures are dominated by mudstones and siltstones with subordinate sandstones, conglomerates and coals. These sediments, their structures and enclosed plant fossils confirm a shifting mosaic of warm, humid, equatorial, lacustrine and alluvial environments (Fulton & Williams, 1988; Bridge *et al*., 1998). Laterally persistent mudstone beds were deposited in lakes, or as brackish-water 'marine bands' during episodes of eustatic sea-level rise. Peat development resulted in formation of coal seams. The Duckmantian Warwickshire Thick Coal, still worked at Daw Mill Colliery north-west of Coventry, formed by prolonged peat accumulation, sometimes as a raised mire (Fulton, 1987).

Late Duckmantian to Bolsovian times witnessed a diachronous shift from Coal Measures deposition to the varicoloured mudstones that dominate the Etruria Formation of the basal Warwickshire Group (Besly, 1988; Powell *et al*., 2000). Thereafter, the Warwickshire Group, ranging up into the Permian, is dominated by sandstones, mudstones and pebble beds of non-marine origin often developed as red-beds (Waters *et al*., 2007). This phase signifies further northward drift into a circum-equatorial arid belt (Besly, 1988).

The Etruria Formation represents well-drained alluvial plain environments (Besly, 1988; Besly & Fielding, 1989). The scarcity of coals and the occurrence of oxidised, colour-mottled and reddened mudstones confirms a shift to conditions of better drainage. The earliest of these rocks occur on the more southerly flanks of the coalfield. Adjacent to the Western Boundary Fault, oxidised mudstone and mud-chip breccia suggest development of a fault-scarp and redistribution of locally derived material into the coal basin by flash floods (Besly, 1988). Near the eastern boundary of the coalfield the Weston Farm Borehole has revealed volcaniclastic lithologies that are possibly contemporaneous with similar rocks in the South Staffordshire Coalfield to the west (Bridge *et al*., 1998).

The overlying Halesowen Formation (Westphalian D) rests on a slightly folded and eroded surface of the Etruria Formation and Coal Measures in the northern part of the coalfield (Fig. 8). It oversteps the Coal Measures to the south, resting on Lower Palaeozoic rocks in the southern part of the coalfield and west of the Western Boundary Fault (Bridge *et al*., 1998). These relationships suggest decreasing influence of the coalfield margin horsts and re-establishment of a regime characterised by gentle subsidence. The Halesowen Formation is believed to have been of southerly derivation, suggesting that the Wales-London-Brabant Massif had been reduced in relief, allowing sediment from the rising Variscan mountains to the south to be swept across it. The lower part of the Halesowen Formation is dominated by thick fluvial sandstones interbedded with coals and palaeosols including calcretes, indicative of a moderately dry climate. Mudstones predominate higher up and include the

Index Limestone. This is a laterally extensive marker bed, probably lacustrine in origin (Powell *et al*., 2000).

The Salop Formation (Westphalian D probably up to Stephanian) is marked by the widespread reappearance of red-beds, signifying a return to relatively well-drained alluvial plain environments. Three overall upward-coarsening members have been recognised, thought to represent prograding alluvial fans (Bridge *et al*., 1998). The lowest, Whitacre Member is dominated by mudstones and sandstones. Locally pebbly Arley and Exhall sandstones dominate the upper part of the member (Shotton, 1927). Red-brown mudstones and thin sandstones also dominate the Keresley Member. The highest part of the Allesley Member has yielded large pieces of silicified wood (Eastwood *et al*., 1923).

The Tile Hill Mudstone Formation crops out within the southern suburbs of Coventry and is probably wholly Late Carboniferous (Stephanian) in age. Above it, the Kenilworth Sandstone Formation crops out north of Kenilworth and is characterised by reddened alluvial sandstones. It has yielded sparse terrestrial-freshwater vertebrate remains indicative of an Early Permian (Autunian) age (Powell *et al*., 2000). Near the base, the Gibbet Hill Conglomerate includes pebbles of Precambrian tuff and Carboniferous sedimentary rocks. Breccia lenses occur towards the top of the formation (Shotton, 1929). Constituting the highest division of the Warwickshire Group, the overlying Lower Permian Ashow Formation is dominated by red-brown mudstones with thin siltstones and sandstones (Shotton, 1929; Old *et al*., 1987). The local succession appears to have been influenced by flash floods depositing sandstones, pebble beds and breccias (Old *et al*., 1987; Smith & Taylor, 1992; Benton *et al*., 2002).

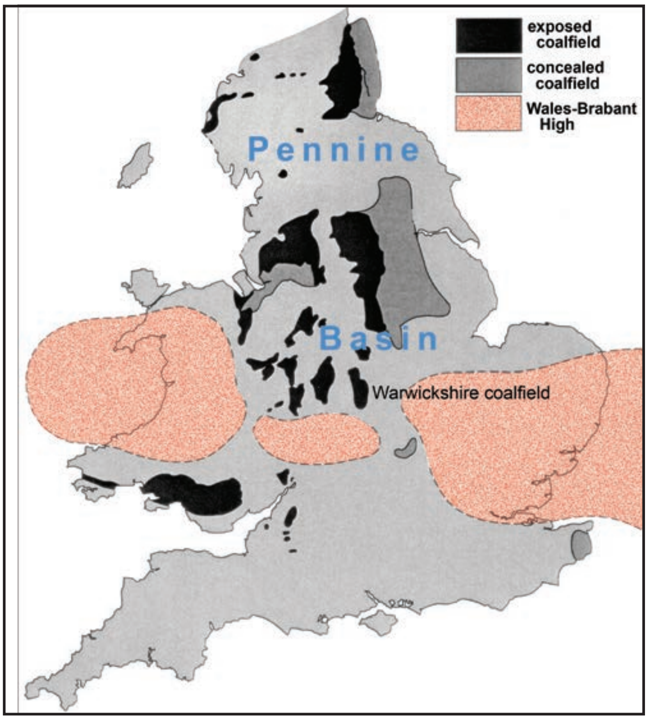


***Figure 10**. British coalfields in relation to the Pennine Basin and Wales-Brabant High (after Powell et al., 2000).*

End-Variscan deformation

The present-day synclinal structure of the Warwickshire Coalfield, involving strata ranging up to the Ashow Group, is largely due to early Permian (late Variscan) regional compression (Bridge *et al*., 1998; Fig. 8). It is likely that the N-S orientation of the coalfield is mainly a legacy of Malvernoid lineaments, notably the Western Boundary Fault (Fig. 2). On the broadest scale the tectonism was a response to deformation farther south involving the suturing of Laurussia and Gondwana along the Hercynian 'megastructure', consolidating the Pangaean supercontinent (Guion *et al*., 2000). Relatively small-scale folds and faults are superimposed upon the overall synclinal structure of the coalfield (Fig. 2). On its northeastern margin, structures with NW-SE orientations are evident. Among these, the Camp Hill Monocline represents a structure along which Carboniferous and older strata steepen progressively towards the Polesworth Fault, bringing the Precambrian and Lower Palaeozoic rocks to the surface within the Nuneaton Inlier. Along the southeastern margin of the Coalfield, the north-south trending Binley Monocline demonstrates a similar structural style (Bridge *et al*., 1998).

Triassic

Late Permian times in central England were marked by east-west crustal extension and rifting associated with early Atlantic opening, resulting in reactivation of favourably oriented basement faults. The succeeding Triassic strata were deposited mainly in the resulting fault-bound basins (Chadwick, 1985; Chadwick & Smith, 1988; Ruffell & Shelton, 2000; Radley, 2005; Fig. 8). These strata continue the trend of non-marine deposition in semi-arid to arid settings at 15-20°N (Ruffell & Shelton, 2000; Benton *et al*., 2002; Radley, 2005). The rocks largely occupy three structural units (Fig. 2). Northeast Warwickshire marks the southwestern part of the Hinckley Basin. To the west, the Coventry Horst was formed by partial tectonic inversion of the Late Carboniferous depocentre, and is characterised by an incomplete, patchy Triassic cover. Along the western edge of the horst, the Western Boundary and Warwick faults mark the eastern margin of the Knowle Basin (Bridge *et al*., 1998).

The Hopwas Breccia and overlying Polesworth Formation (Sherwood Sandstone Group) represent the oldest part of the Hinckley Basin fill. The breccia appears to be talus derived from the nearby horst margin and deposited in basin-margin fans. The Polesworth Formation includes typical 'Bunter' pebble beds, deposited by fast-flowing braided rivers. Among the pebbles, the abundant quartzite clasts appear to be derived mainly from the region of the Armorican massif (Brittany-Cornwall), by a large river system (the 'Budleighensis River' of Wills, 1956) draining north and northeast through the Worcester Basin (Warrington & Ivimey-Cook, 1992).

Figure 11. Southam Cement Works Quarry, Long Itchington, before it was flooded. Low faces in the foreground are of limestones of the latest Triassic (Rhaetian) Langport Member; the cliff in the background (about 30 m high) exposes part of the Early Jurassic Blue Lias Formation comprising mudstones of the Saltford Shale Member, overlain by alternating mudstones and paler limestones of the Rugby Limestone Member.

The Bromsgrove Sandstone Formation is the oldest Triassic unit to overstep the major coalfield boundary faults onto the Coventry Horst (Fig. 7). On the southern end of the horst, in the Warwick district, the Bromsgrove Sandstone rests unconformably on Early Permian red-beds. There it is characterised by sandstones with subordinate red-brown mudstones of alluvial origin that have yielded an internationally important freshwater-terrestrial vertebrate fauna (Old *et al*., 1987; Benton & Spencer, 1995). The sandstones and immediately overlying strata are the principal source of the spa waters at Leamington.

The Bromsgrove Sandstone fines up into the Mercia Mudstone Group through a sequence of sandstones, siltstones and mudstones (Tarporley Siltstone Formation; formerly 'Passage Beds' and 'Waterstones'), reflecting a broad alluvial plain and the regional breakdown of the river systems. The overlying Sidmouth Mudstone Formation (representing the lower part of the Mercia Mudstone Group; Howard *et al*., 2008) is dominated by unfossiliferous red-brown mudstones and siltstones, locally interbedded with siltstones and fine-grained sandstones. Nodular and vein gypsum has been encountered in boreholes. Most of the Mercia Mudstone is an accumulation of wind-blown dust (Arthurton, 1980; Jefferson *et al*., 2002), forming on a broad, low-lying sabkha. Laminated units possibly signify deposition in playa lakes, though much of the sediment probably accreted on extensive wind-swept flats that were damp due to a high, saline water table. This high water table resulted in the precipitation of gypsum close to the sediment surface; some may have formed within hypersaline lakes (Warrington & Ivimey-Cook, 1992). Thin siltstones and sandstones within the mudstones were formed by rapid runoff from flash floods (Powell *et al*., 2000).

Within the upper part of the Mercia Mudstone Group, the Late Triassic (Carnian) Arden Sandstone Formation is present as pale sandstones and siltstones with varicoloured mudstones. Unusually for the Mercia Mudstone Group, a number of fossils have been found, including land plants, molluscs, crustaceans, fish remains and amphibians, invertebrate burrows and reptile trackways (Old *et al*., 1991; Benton *et al*., 2002). The palaeontological and sedimentological evidence suggests an estuarine or deltaic setting, with the thicker sandstones representing distributary channels or a short-lived river system. The formation reflects a connection with southern, Tethyan marine sources (Radley, 2005). Ultimately, Warwickshire reverted to the essentially continental environment with flash-floods, playa-lakes and possible marine incursions, in which the red-brown mudstones of the Branscombe Mudstone Formation accumulated (Warrington & Ivimey-Cook, 1992; Howard *et al*., 2008). Forming the highest part of the Mercia Mudstone Group, the overlying Blue Anchor Formation comprises grey-green mudstones and siltstones. Scattered microplankton indicates increasing marine influence, prior to the Rhaetian transgression (Warrington & Ivimey-Cook, 1992).

In contrast to the Mercia Mudstone, the Rhaetian Penarth Group is characterised by fossiliferous mudstones, siltstones and limestones, some of fully marine aspect, that are subdivided into the Westbury and Lilstock formations. At the base, the Westbury Formation comprises laminated grey mudstone yielding molluscs, fish remains and other marine fossils. Slump structures attributed to seismic shock have been recorded at the top of the formation (Simms, 2003). Representing the lower part of the overlying Lilstock Formation, the Cotham Member is dominated by sparsely fossiliferous calcareous mudstones and siltstones (Old *et al*., 1987). East of southern Warwickshire's Stour Valley, the Cotham Member is succeeded by the Langport Member, the highest division of the Penarth Group (Fig. 11), dominated by pale, fine-grained limestone that yields a shelly fauna (Swift, 1995). Both the Cotham and Langport members are ascribed to shallow-water, marine or quasi-marine environments (Old *et al*., 1987).

Jurassic

South of the coalfield, in Early and Middle Jurassic times the north-south trending (Malvernoid) Vale of Moreton Axis separated the London Platform and East Midlands Shelf in the east from the Worcester Basin in the west (Fig. 1). Southern Britain is thought to have laid roughly 10° south of its present latitude during the Jurassic, among a complex of seaways generated by crustal extension within the northwest European sector of Pangaea (Hesselbo, 2000). The presence of corals, thick-shelled mollusks, ooidal limestones and ironstones within the Warwickshire succession show that climates were warm and sometimes humid.

The Jurassic of Warwickshire was reviewed by Radley (2003). The strata range up to the Bathonian Stage of the Middle Jurassic. They comprise two overall upward-shallowing marine successions deposited under regional tectonic control, superimposed upon a picture of general sea-level rise following the latest Triassic - earliest Jurassic marine transgression. Each major shallowing succession is dominated by mudstones of offshore, relatively deep-water origin (Blue Lias, Charmouth Mudstone and Whitby Mudstone formations), passing up into shallow-water sandstones, limestones and ironstones (Dyrham and Marlstone formations; Inferior and Great Oolite groups). The picture is further complicated by a number of minor shallowing and deepening events of local to regional extent, evidenced for example by relatively localised erosion surfaces and facies changes (Radley, 2003).

The first upward-shallowing succession is represented by the Blue Lias (Fig. 11) and Charmouth Mudstone formations, passing up via the arenaceous Dyrham Formation into the ooidal ironstones of the Pliensbachian Marlstone Rock Formation (Radley, 2003). The second succession, commencing with the Whitby Mudstone Formation, concluded with deposition of Middle Jurassic limestones and sandstones (Radley, 2003). Above the Marlstone Rock Formation, the abrupt reappearance of ammonite-rich mudstones at the base of the Whitby Mudstone (Fig. 12) indicates Early Toarcian deepening, thought to have had a tectono-eustatic cause (Hallam, 2001).

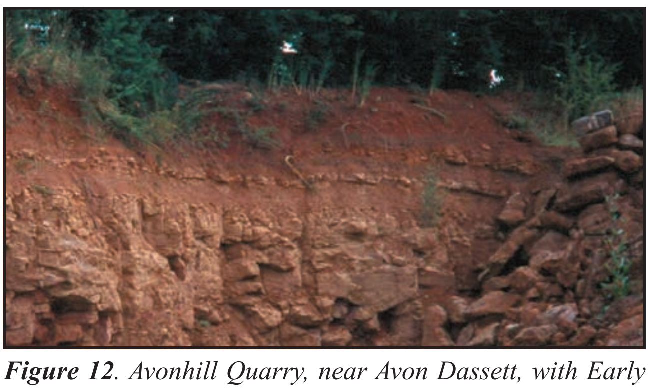


***Figure 12**. Avonhill Quarry, near Avon Dassett, with Early Jurassic Toarcian basal Whitby Mudstone Formation overlying the Pliensbachian possibly up to Toarcian Marlstone Rock Formation, in a face 5 m high.*

Much of the Jurassic succession is richly fossiliferous. Mudstone-dominated formations, in particular, contain many biostratigraphically-important ammonites and historically have also yielded abundant marine reptile remains. Among these, the Blue Lias Formation, exposed in cement quarries (Fig. 11), provides evidence for subtle variations in water-depth and benthic oxygenation. The shallower-water facies developments of sandstones, shelly and/or ooidal limestones and ironstones commonly yield rich benthic faunas including many brachiopods, molluscs and echinoderms. Bioturbation is common throughout much of the Warwickshire Jurassic; notable exceptions are the finely laminated limestone and mudstone developments within the Blue Lias Formation (Ambrose, 2001; Radley, 2003).

The Vale of Moreton Axis clearly affected Jurassic deposition, coinciding with a number of lateral lithological and thickness changes within the local succession. Notable amongst these are the development of sands at the top of the Whitby Mudstone Formation west of the axis region. The London Platform also exerted a strong influence on deposition, evidenced for example by the development of Aalenian arenaceous strata (Northampton Sand and Grantham formations) in the south and east of the county (Radley, 2003).

Cenozoic

Younger Mesozoic rocks are absent in Warwickshire. Upper Jurassic and Cretaceous strata not far to the south (Oxfordshire) provide evidence for a further 100 million years of periodic marine inundation, minor tectonism and a drift towards 42°N (Warwickshire). It seems likely that the area was subject to uplift, tilting and erosion during the Palaeogene and Neogene (Green *et al*., 2001; Carney, 2007; Lane *et al*., 2008), shaping a precursor to the modern landscape.

The Pleistocene and Holocene are marked less by deposition and more by weathering and subaerial erosion in alternating cold and warmer spells which have further altered the precursor landscape. The oldest sediments constitute the Middle Pleistocene 'Wolston Series'; elucidated stratigraphically by Shotton (1953). These are well-known from sites between Stratford-upon-Avon and Rugby where they trace the line of Shotton's broad, shallow 'proto-Soar' valley. The earliest, fluvial deposits (Baginton Formation) are dominated by sand and gravel (Fig. 13) and record the northeasterly flow of a low-sinuosity braided river ('Bytham River' of Rose, 1994) through the region to Leicester and beyond, which reached the sea near present-day Lowestoft (Rose, 1989).

Near Bubbenhall, south-east of Coventry, the lower part of the fluvial Cromerian Baginton Formation has yielded a number of Palaeolithic stone tools and is locally underlain by temperate fossiliferous channel-fills cut into Mercia Mudstone bedrock (Shotton *et al*., 1993; Keen *et al*., 2006). The fluvial deposits are

Figure 13*. Middle Pleistocene sediments at Wood Farm Quarry, near Bubbenhall. Gravels and sands in the lower part of the section represent the Thurmaston and Brandon members of the Baginton Formation, and are overlain by clayey till, the Thrussington Member of the Wolston Formation, in a face 6 m high.*

overlain by Thrussington Till rich in Mercia Mudstone (Fig. 13). This is now interpreted as signifying the onset of the Anglian glaciation (Maddy, 1999), involving ice advance up the 'proto-Soar' valley from the north (Sumbler, 1983).

Above, the laminated Wolston Clay and associated fluvial deposits suggest glacio-lacustrine deposition following glacial retreat. Shotton's (1953) concept of a glacial 'Lake Harrison', covering extensive areas of the Midlands, has been weakened in recent decades. Firstly, the presence of till layers within the Wolston Clay suggests the proximity of an ice sheet that would have exerted a strong influence on lacustrine deposition. Secondly, it seems likely that the Wolston Clay lacustrine deposits are at least partly diachronous. Thirdly, a putative lake shoreline bench, identified by Dury (1951) in southern and eastern Warwickshire, is now attributed to a resistant marker bed within the Early Jurassic Charmouth Mudstone Formation (Ambrose & Brewster, 1982). Accordingly, Shotton's concept of a single widespread lake has been superseded by a new model involving diachronous development of transient lakes and ponds, associated with ice sheets advancing from the north and east (Sumbler, 1983; Old *et al*., 1987).

A second ice advance later in the Anglian saw deposition of the Oadby Till, a dark grey till formed from Jurassic and Cretaceous rocks and noted for the abundance of flint and chalk erratics. This was formed by ice advancing from the north-east. The flint-rich Dunsmore Gravel of eastern Warwickshire, capping the glacial succession, was deposited possibly from meltwater derived from the decaying Oadby Till ice sheet (Shotton, 1953; Old *et al*., 1987; Keen, 1999). This glacio-fluvial depositional phase has been linked to the early establishment of the Avon Valley drainage system (Sumbler, 1983; Keen, 1999). Elsewhere, Anglian glacigenic deposits form a thinner, patchy cover on the Coventry Horst (Old *et al*., 1987; Bridge *et al*., 1998) while south of the Avon Valley, tills are largely restricted to the interfluves and scarp tops. In the west of the county, west of the Kingswood Gap, the glacial deposits are of western origin. Welsh igneous rocks occur (Tomlinson, 1935) with a greater variety of rocks found further west including Welsh and Uriconian igneous and Carboniferous lithologies (Old *et al*., 1991).

River terrace deposits dominated by pebbly sand are widespread in the Avon Valley. They post-date the earlier glacial and fluvial-glacial deposits (Keen, 1999), and indicate further uplift. The Middle Avon flows southwest, roughly parallel to, but incised below the course of the old north-easterly flowing proto-Soar. Below Stratford-upon-Avon it formed a broad belt of palaeomeanders now represented as the 3rd Terrace and dated to MIS 5 (Maddy *et al*. 1999). Alluvium is widespread along the modern valleys.

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Amber from the Baltic

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Abstract: Amber has been prized for its gem and mythical properties for centuries. Its primary source is the Baltic coast of Poland and Kaliningrad. The fauna and flora found in Baltic amber relate to the climatic changes in the late Eocene, when the amber was formed during a period of warmer temperatures. Amber was extracted by "fishing" on the coast, and is now won by modern opencast mining at Yantarny on the Samland Peninsular of Russia. Amber is used to make ornamental jewellery and other products, but it is difficult to distinguish genuine amber from various substitutes, particularly copal.

Neolithic sites along the Wistula River have testified that Baltic amber has been richly prized for thousands of years, and has been traded for its ornamental value, with exports to the ancient world. The Greeks were aware of its static electrical properties and their name for amber, *Elektron*, gives us our name for electricity. Amber was correctly identified by Pliny the elder as fossilized tree resin and Tacitus mentioned in the second century AD that it was extensively worked for jewellery in Aquileia (near Trieste). Amber objects have even been found in Bronze Age sites in Britain, such as the Hove Cup, excavated from the Clandon Barrow in 1857 and now in the Brighton Museum. Since amber burns with a distinct sweet smell, it was also used as an incense, together with copal, frankincense and myrrh, which are all related materials, and it soon gained mythical and supernatural properties. Tacitus mentioned the Amber Islands, close to a large river in which the amber was found. With the arrival of the dark ages in western Europe, amber's true origin was largely forgotten. Medieval, and later, chroniclers described legendary islands from which the amber came, and suggested that amber was either the fossilized tears of the innocents who were drowned in Noah's flood, or fossilized sunbeams. Since the Middle Ages much was written on its medical and healing properties, particularly for disorders of the throat, "flux of the belly", poisoning and, according to Camellus Leonardus writing in 1502, "if laid upon a wife when she is asleep, will make her confess all her evil deeds". Small chips of amber are made into spider webs that are still hung in the rafters of cottages in some parts of Poland because of the alleged healing powers.

Wave-rolled amber with bark fragments (photo: Museum of the Earth, Polish Academy of Science [MEPAS]).

In the 18th century, scientists took an interest in amber, and started to investigate its real origins. Though not technically a mineral in the classic sense, it is often classified as a gemstone in the jewellery industry. The name (in English and Latin) is derived from ambergris, the waxy deposit secreted by sperm whales, which was then washed up on beaches and was purified to produce perfumes. Amber was considered to be a fossilised version, and it was also refined to produce a sweet amber oil that is still used in some products today.

Away from the major Baltic locations, amber is found worldwide, notably from Canada to Central America. Some of the world's largest deposits are mined in the Dominican Republic, in China, and in many countries of Europe. The oldest amber yet found is Upper Carboniferous and the oldest insects are preserved in Lower Cretaceous material. One insect-bearing deposit occurs within the Wealden sequence on the Isle of White. The youngest amber, dating from about 20 Ma, is found in Switzerland.

Amber necklace of about 100 BC from near Gdańsk (photo: Archaeological Museum Gdańsk).

Composition of amber

Amber is a generic term for a variety of fossilised resinous and bituminous substances extruded by conifers, with a general formulae simplified to $C_{10}H_{16}O$. Although of heterogeneous composition, most of these substances are bituminous and insoluble in water, but are soluble to a greater or lesser extent in alcohol, ether and chloroform. Younger material contains varying amounts of succinic acid, which crystallises over time, with an increasing loss of volatiles, through polymerization. While large, fairly pure, masses of late Tertiary amber can break with a conchoidal fracture, older amber from the Cretaceous tends be very brittle and will easily shatter.

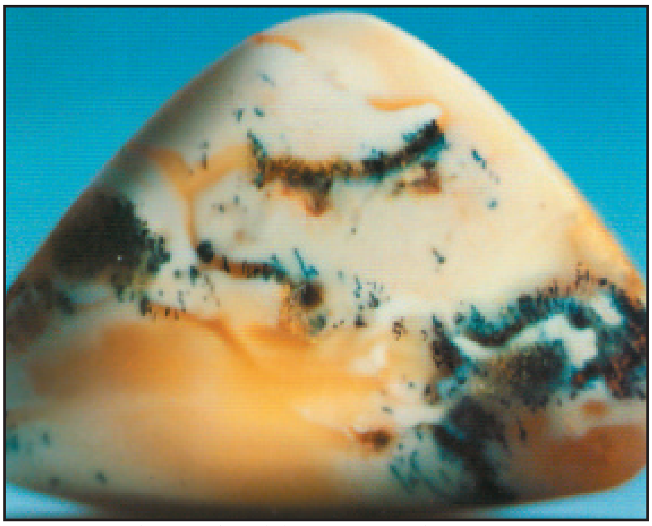
Amber varies in colour from clear to dark red, with the well-known, rich, reddish yellows favoured for the production of jewellery. Bluish and dark brown varieties, sometimes called black amber, are also known. A variety sometimes prized as a gemstone, is succinite [containing 3-8% of succinic acid, $COOH(CH_2)_2COOH_{15}$], and the best of it comes from the Baltic area; its colour is white or a pale transluscent yellow, due to microscopic inclusions of trapped air. Other varieties based on their chemistry include gedanite (a resin containing much less succinic acid) and then various varieties of retinite, which contain up to 6 % oxygen but no succinic acid. Gedanite tends to be lighter and more brittle than succinite, so is less favoured by jewellery workers since it is difficult to work. Beckerite is much denser and harder than gedanite, despite being found in associated deposits. It takes a poor polish but does not break as easily.

The density varies according to the amount of trapped air bubbles and impurities; amber will sink slowly in still water, but can become suspended in agitated water, particularly saline water. Highly weathered (oxidized) amber is lighter and can float. It was formally thought that identification of the amounts of succinic acid could be used to allow ambers to be identified and dated; Baltic ambers usually having high proportions compared to other sources. This technique, only partly successful, has now been replaced by more sophisticated infrared and mass spectroscopy techniques.

Polymerization in amber results in macromolecules that give a high impermeability to water-based fluids, though micro porosity can occur and allow the escape of volatiles. Objects found in amber are preserved by being totally sealed rather than fossilised (i.e., there is no replacement by mineralization), which results in a very high level of preservation of the contents.

hardness (Mohs' scale)	2 – 2.5
density	1.05 – 1.96 Mg/m^3
streak	white
refraction index	1.54
melting point	250 – 300 ºC

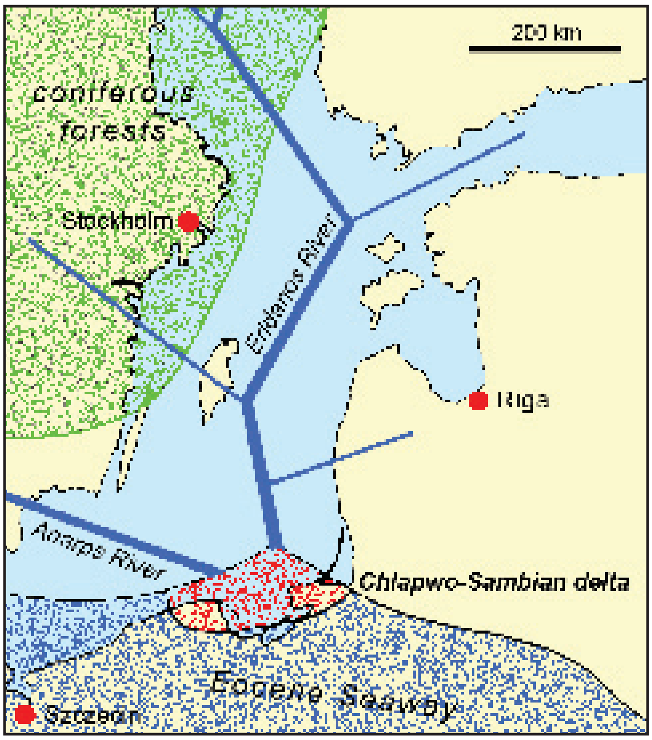
Physical properties of amber



Succinite, white amber (photo: MEPAS).

Baltic amber: occurrence and origin

The southern Baltic region contains one of the world's largest resources of amber, and extends around the coastal areas of the eastern part of Poland, through the Kaliningrad Oblast (a detached enclave of Russia between Poland and Lithuania), and into the southwestern corner of Lithuania itself. Within the Kaliningrad enclave, the primary amber locations are on the Samland Peninsular. In Eocene times, this whole region was occupied by the Chłapwo-Sambian delta of the Eridanos and Anarps rivers, which together drained much of Scandinavia. The main streams appear to have followed fault lines, now occupied by the Kattergat and gulfs of the Baltic Sea, and flowed into a combined



The Eocene amber-bearing river system that carried the resin from its Scandinavian forest source to its Baltic delta (after Jaworowski and Holst).

A chunk of amber weighing 1.5 kg in the museum at the old factory in Yantarny.

delta in the area of today's southern Baltic. This delta formed on the margin of an Upper Eocene Seaway that extended from an enlarged North Sea, southeast across Europe, following the Tonquist line, to the Middle East. Two more deltas into this seaway, now lie buried to the southeast of the Baltic - the Parczew delta in east central Poland and the Klesev delta in the Ukraine. They also produce small amounts amber of similar age.

[Left] Fossil tree bark with tunnels of bark-boring beetles filled with amber resin (photo: MEPAS).

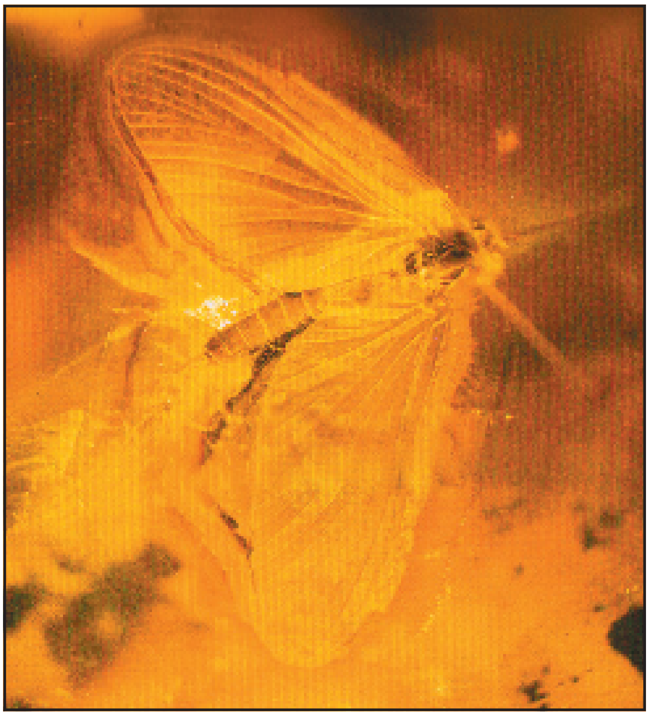
[Right] Drps of resin seeping from a scar on a modern spruce tree (photo: Emmanuel and Anna Boutet).

The resin-producing conifers grew within these rivers' catchment across most of Scandinavia and parts of western Russia. As the trees died, they were washed into the rivers and eventually to the delta where they were rapidly buried. Some of the wood rotted away, though much is preserved as lignite, but the resin survived because it changed to amber under the anaerobic conditions of diagenesis.

There is some controversy regarding which trees were responsible for the resin that formed the amber, principally since few trees today contain succinic acid in their resins. In the 19th century it was assumed that only one species, *Pinites succinifer,* was responsible; more recently it has been suggested that several species, possibly related to an ancestor of *Psudolarix kaempferi,* the Golden larch, now found only in Eastern China, are likely contenders. It is thought that gedanite may be from a totally different tree due to its low content of succinic acid.

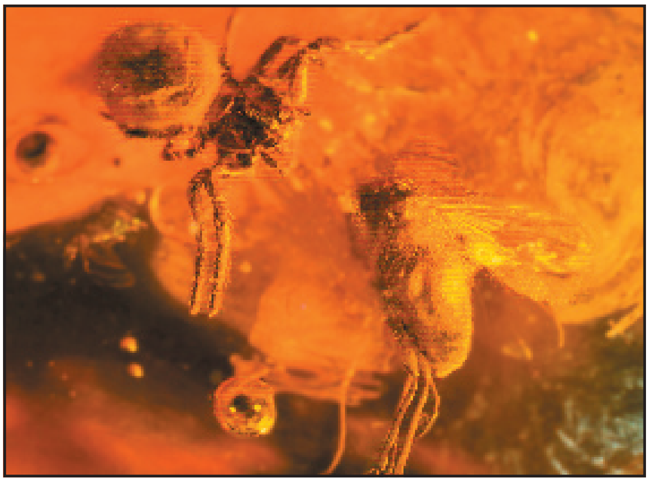
Resin, not to be confused with sap (a mixture of water and sugars on which the tree lives), normally only exudes from the tree when it is under attack. Sea levels were high in the Eocene in response to the high temperatures of the Thermal Optimum around the Palaeocene-Eocene boundary. Although Baltic amber ranges in age from 35 to 45 Ma., about 10 Ma later than the Thermal Optimum, there were numerous strong oscillations of sea level at this time associated with blips in the general post-Optimum cooling trend. It is thought that the trees became stressed as the water table rose or fell during one or several such oscillations, leaving the trees more venerable to fungal and insect attack. This theory is supported by the situation in the Coast Range mountains of British Columbia today. There, many trees in the extensive highland pine forests are being rapidly killed by a fungus introduced by the pine weevil. In this case, dryness and warm winters have stressed the trees, and warmer winters are not killing the larval stages of the weevil. The infected trees extrude resin as a defence mechanism against the weevil. Evidence for similar stress in the Eocene amber forest lies in the large quantity of amber resin impregnated with worm holes and fungal debris. Many of the amber drips exceed 20 cm in length.

Polished pebble of amber containing an ant and various plant fragments (photo: Tony Waltham).



Mayfly, Ephemenoptera*, in Baltic amber (photo: MEPAS).*

Since the 17th century, scientific interest, made possible with improvements in microscopes, has focussed on the contents of the amber, particularly the great variety of insects and other small animals it contains. The most common animals found are insects, arachnids and myrapods, but small amphibians and a lizard have also been recorded. It is little wonder that the state of preservation led to the science fiction accounts of extracting DNA to recreate the dinosaurs in "Jurassic Park". Apart from indicating the inhabitants of the amber forests, their occurrence has suggested climatic changes since the deposits formed. Evidence for the local late-Eocene climate being generally warmer than today is provided by the many insects and beetles that are temperature sensitive; notably, the termite *Isoptera* occurs in the amber, but is now only found in tropical regions.



Spider, Aranea *sp., near its victim fly,* Diptera nematocera, *both encased in amber (photo: MEPAS).*

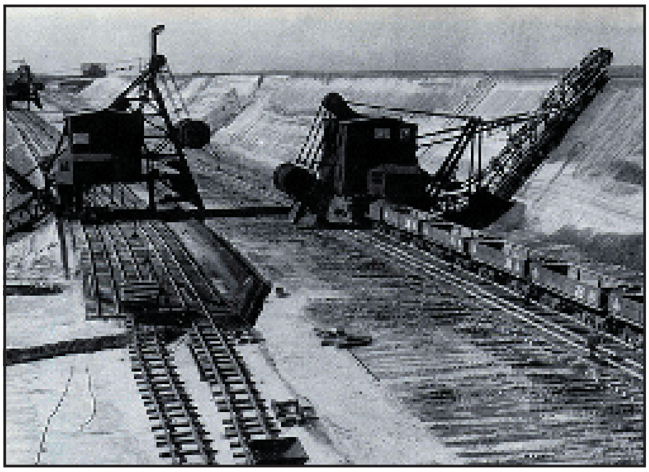
Fishing for amber after a storm, on the sand beaches of the Samland Peninsula during the 1930s.

Amber mining on the Baltic

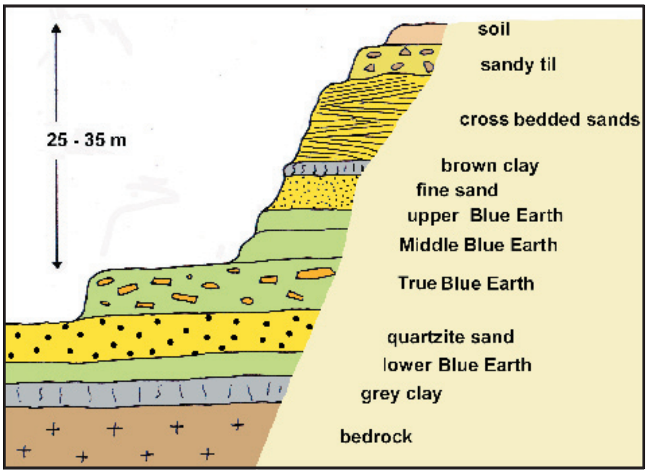
Until the 19th century, most amber was picked up from the sea shore of the Baltic. Due to its low density, it was easily dispersed by storms after being ripped from submarine outcrops and then transported landwards and westwards. Pieces of amber weighing around a kilogramme have even been found on the beaches and in offshore dredging along the Norfolk and Suffolk. Pleistocene glaciers also re-distributed amber across northern Europe; some notable finds in glacial deposits include a piece weighing 3 kg in sandy till near Tochula, central Poland. It is likely that such finds would have supplemented the amber industry in Neolithic times.

It was the Prussians who really put amber production onto an industrial scale, when they controlled the whole of the southern Baltic coast. Amber extraction from a buried Holocene beach, 12 m deep, still continues today in the Gdańsk area of Poland. However, the biggest area for amber production is the Samland Peninsula, once part of Prussia and then within Germany until 1945. In the 16th century the coastal area of the peninsula was cordoned off to try to monopolise the industry. Fishermen were employed with large nets to catch the amber in the surf when the winds were right. Today, these beaches on the peninsular and along the Baltic side of the Kursskaja sand barrier are a popular tourist destination for the Russians. One of their great pastimes is to look for amber, with the best time being after a storm, but pickings are small today.

Yantarny and the Samland Peninsula.



Overburden stripping at the Palmnicken mine in the 1930s.



Sketch section of the amber-bearing sediments at Yantarny.

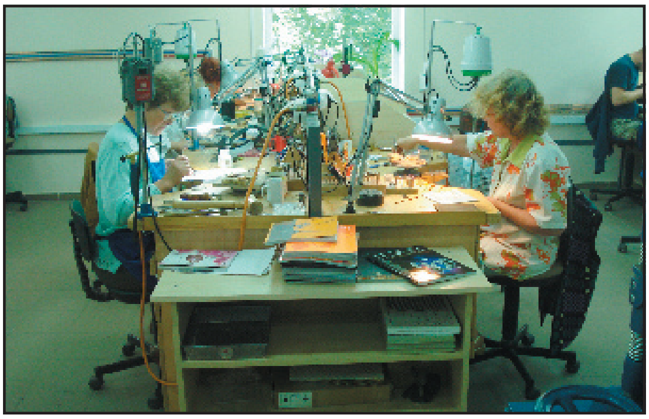
In the mid-19th century, Messrs Stantien and Becker started to dredge for amber in the Kursskij Lagoon, behind the Kursskaja sand barrier on the north side of the Samland Peninsula. In 1875, they opened a mine just south of the Prussian town of Palmnicken (later renamed Yantarny, from the Russian word for amber); originally a small fishing village, its population rapidly expanded with the workopportunities in the amber industry. They eventually built their own Protestant miners' church in 1891, and today it is one of the few churches that is restored and used as an Orthodox church in the Kaliningrad Oblast. The original mine entrance was close to the beach, and during a storm surge in 1892, sea water flooded into the mine, drowning six men who were unable to escape.

A large opencast mine was then worked to reach down to the Blue Earth (a translation of the German *Blauerde*) that contains the amber. Even by 1930, the process of excavation had become very mechanised, with large draglines and bucket chain excavators removing the overburden. This pit was originally very profitable, as it yielded up to 3 kg of amber per cubic metre of the ore bed. It was abandoned when the overburden ratio rose to uneconomic levels, and the pit remains today as a lake 2 km long just to the north of town. The mine site and the nearby sea shore gained a notoriety as a war crime location at the end of the war, when 15,000 inmates from the Stutoff concentration camp, near Gdańsk, were marched there to be walled up in the disused mine workings. When the manager refused to comply with the wishes of the Gestapo, the prisoners were all marched into the sea and shot.

Today the Plazhovaya mine is a large opencast site, just to the east of Yantamy, which now boasts a population of 6000. Visitors are escorted (security is everywhere in this part of Russia) to a viewpoint overlooking the kilometre long active face of the quarry. Working eastwards, the miners are encountering increasingly deeper overburden, though the deposits themselves dip slightly to the west. The Blue Earth, the source of the amber, is a sandy silt that is greenish when fresh, due to high levels of glauconite. All three Blue Earths contain amber, and the Middle Blue Earth contains a large quantity of lignite from the forests. The main and richest layer, the True Blue Earth, varies in thickness from 17.5 m down to nothing, and yields up to 2 kg of amber per cubic metre in the current workings. Iinformation on the lifetime of the pit and any other geological data are all kept very secret. Within the mine, the Blue Earth is exposed by draglines that remove the barren overburden. The amber is then washed from the clay by high-pressure water jets from powerful monitor pumps, and where conditions allow the pumps are installed to wash the soil directly from the outcrop. Although about 600 tonnes of amber are produced annually at Yantarny, only about 10% of this is of gem quality, and less than 1% has preserved animal remains.

Current working in the Plazhovaya amber quarry at Yantarny, with three draglines along the main face that is partly hidden by the spoil heaps of overburden.

A piece of amber within the Blue Earth matrix.



Sorting amber and making jewellery in the Yantamy factory.

Amber as a precious stone

Baltic amber's translucence, and the remarkable state of preservation of its contents, has meant that it has been one of the most highly prized gemstones used in jewellery for centuries. This is particularly the case for the red translucent varieties. Various small factories were established by the Prussians in the 19th century to sort and produce amber jewellery and souvenirs, though some was still produced by individual craftsmen. The main Prussian production areas for producing amber goods were Köningsberg (Kaliningrad) and Danzig (Gdańsk), which were both important Baltic trading cities. The industry collapsed during both World Wars, when export through the blockaded Baltic became a problem. After 1945, the Russians revived the industry and, for security reasons, concentrated jewellery production into one large factory at Yantarny. This recently closed, but today it houses a museum displaying a whole variety of ornaments from pictures of Lenin to model churches, boxes and of course, jewellery, all made from amber. Security at the factory is extremely tight. Visitors are searched going in and coming out, and photography of the derelict buildings, outside the museum room, is strictly forbidden.

A modern private factory has recently opened to the north of the town, where the processes of sorting amber and making jewellery can be observed and photographed, albeit through glass screens. Total Baltic amber output is estimated to be 800 tonnes annually. Russian output remains static, but greater Polish output from the Gdańsk mine is slightly increasing the total.

From the Renaissance onwards, amber has also been used as a decorative addition to pieces of furniture. Of historical note is the famous Amber Room, commissioned by King Fredrick of Prussia in 1701, for his palace in Berlin, which he later presented to Czar Peter I of Russia in 1716 to confer a friendship treaty between the two countries. The Amber Room was the largest work of art ever made out of amber. It consisted of 100,000 pieces of carved amber, accented with diamonds, emeralds, jade, onyx and rubies. Amber panels covered an entire room of 55 square metres, and they weighed more than six tonnes. They were backed entirely in gold leaf, and it took a team of craftsmen ten years to create. The room was eventually installed in Catherine Palace, outside St. Petersburg, and was enlarged by Catherine the Great, when many semi-precious stones were added. Captured by the Germans in World War 2, it was taken to Köningsburg

Necklace of pebbles of amber that each contain insects.

The Amber Room in the Catherine Palace at St. Petersburg, as it was before World War Two.

Amber casket that was made in the 18th century.

(Kaliningrad) and displayed in the Castle in November 1941, but this was heavily damaged by British bombing in 1944. The Russians maintain that when they arrived in March 1945 the Amber Room had disappeared. Despite much accusation and argument, no fragment of the room has ever been found, and it remains one of the world's greatest lost treasures. It is possible that it was dismantled, packed and placed on the ill fated *Wilhelm Gustloff*, a ship carrying refugees that was torpedoed after leaving Köningsburg in January 1945. However the hunt is still on and treasure hunters keep claiming to have found bits of it hidden at various locations in the pre-war German domain.

Between 1979 and 2003 an exact replica of the Amber Room was built, also within the Catherine Palace, with amber supplied by the mine at Yantarny.

Modified and fake amber

Following its mythological association with ambergris, much of the lower grade of amber is retorted to produce small quantities of amber oil for use in perfumes. About 2% of succinic acid can be also recovered, which is used in medicines and dyes. The residue, a dark pitch, can then used to produce a hard varnish, which has good waterproof properties, similar to copal varnish, but harder. This was traditionally used to varnish violins in the 17th century. Like amber, copal is also a semi-fossilised resin, but it is less diageneticly altered than amber so contains more volatiles, in particular the terpenes, which make it softer.

Amber casket on display in the amber museum within the old factory at Yantarny.

With its low melting point, it is easy to form amber liquid, and then to cast jewellery with it. Some of this processed or fake amber is quite obvious; modern house flies entombed in amber drops are commonly sold on stalls in Tallinn, Estonia, and many small animals such as frogs are incorporated into South American amber where faking is rife.

Much more cunning is the manufacture of items shaped from pressed poor quality amber after heat treatment to improve, darken and redden its colour. Generally the rich red varieties are preferred for jewellery. Much of this faking or "improvement" was formally done legally with the cooperation of the Russian authorities, but since 2002 the practice has been outlawed in Russia and Poland following a Russian-Polish-German conference of amber investigators in June 1996. Supplies of inferior amber are now regulated to prevent them being substituted for gem quality material, and security at the mine and factories is very tight in order to control theft. However, this 'ambroid' is still sold on street stalls all round the Baltic coast, and there are also many artificial plastic substitutes. The problems with antique amber are complicated since the Victorians experimented with bakelite, a variety of plastic that was used to imitate amber in the 19th century. Such items have now developed a patina of age that makes them difficult to distinguish from genuine amber with its own patina.

Many items reporting to be amber are in fact copal. The two can be distinguished by inserting a hot needle into the specimen. Copal melts easily and gives off a sweet smell, while true amber melts more slowly and produces a black smoke. Alternatively, acetone does not affect amber, but a few drops of it will start to dissolve the surface of copal, so that it becomes sticky. Amber will also not cut easily (it tends to flake and shatter) while many substitutes, particularly plastics, will produce shavings. It has been suggested that over half the 'genuine' amber in museums, as well as in high class vendors, is faked to some extent, so the old epithet of "buyer beware" remains very appropriate.

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A Vanished Industry: Coprolite Mining

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Abstract: Phosphatic nodules, generally known as coprolites, occur mainly in the Cretaceous clay formations which outcrop in a SW-NE belt from Norfolk to Oxfordshire with outlying patches in Yorkshire and Kent and in the early Pleistocene of Suffolk. They were exploited commercially in Victorian times as source of phosphate for what was then called "chemical manure". Working this resource of fertilizer made a substantial contribution to British agriculture in the 19th century.

The early 19th century saw the recognition that the application of fertilizers, particularly those rich in bone meal, to agricultural land led to a significant improvement in crop yields. About 1827 the German explorer Humboldt returned from South America to Europe and his report led to Europeans discovering the beneficial effects of "huano", better known as guano, as fertilizer. Guano consists of phosphate-rich bird droppings with fish bones and other remains which formed an accumulation on the Chincha Islands off the coast of Peru. Large quantities were shipped to European ports such as Liverpool. Analytical chemists soon showed that the particular benefits as fertilizer came from phosphate, and a search was begun for cheaper and less distant sources. One deposit was already being exploited – the Red Crag of Suffolk and Essex, though the nature of its phosphatic content was not fully appreciated at first and the material was regarded as fossil bone-meal. Other sources of bone-meal were occasionally exploited including mummified cats from Egyptian tombs, the shavings from bone-handled knives in Sheffield, the wealth of bones on European battlefields such as Waterloo, and Italian catacombs. With the growing urban population in England's cities there was increasing demand for food and thus for fertilizer.

William Buckland

The term coprolite was introduced about 1829 by William Buckland, the first professor of Geology and Mineralogy at Oxford University, with reference to phosphatic nodules he had found in the Lower Jurassic rocks of Dorset and Gloucestershire. It was derived from the Greek *kopros* (= dung) and *lithos* (= stone). Coprolites had been collected earlier on the continent but were mistakenly regarded as some sort of fossil fir cone. In 1823, Buckland investigated the small Kirkdale Cave in north Yorkshire where he deduced that the bones of such animals as rhinoceros had been brought in by hyenas (both animals were extinct in Britain) and that they were not relics of Noah's Flood as previously supposed (Buckland, 1824, 1829, 1836; Duffin, 2006). He also noted that there were white ball-like objects in the cave and that these were probably hyena faeces. He was struck by the resemblance of these objects to *Album graecum*, a substance used by apothecaries for medical purposes. *Cara alba* was an equivalent material derived from dog excrement and used for heart conditions! In spite of his recognition of the excremental nature of the objects, it was not until several years later that Buckland coined the term coprolite when he collected specimens from the Rhaetic Bone Bed; he called these *Nigrum Graecum* from their black colour (Duffin, 2006). Buckland also obtained faeces from a hyena in a local menagerie for comparison. He spent several of his holidays at Lyme Regis on the Dorset coast where he met Mary Anning, then actively excavating ichthyosaur remains from the Lias for sale to the growing number of museums and other academic collectors. He noted that some associated nodules (locally called bezoar stones) had spiral markings and pointed ends and realized that they could be excreta, comparable to the objects he had found in the Rhaetic Bone Bed. Some were even found inside the pelvic regions of fossil ichthyosaurs, fossilized before evacuation! He realized that some of the excreted nodules contained the indigestible remains of ichthyosaur's prey, chiefly comminuted fish bones, scales and teeth as well as juvenile ichthyosaurs and cephalopod hooks. Thus Buckland founded the coprolitic branch of palaeontology. At his home in Oxford, Buckland was also noted for serving visitors with meals made from unusual animals such as crocodiles, and had a coprolite side-table made to amuse his guests: it comprised polished sections through both coprolites and septarian nodules set in a "cement" matrix and a wooden frame (Fig. 3): it is now in the Philpot Museum at Lyme Regis. The source of the septarian nodules is unknown but they might

Figure 1*. Coprolites from the Red Crag (photo: Sedgwick Museum).*

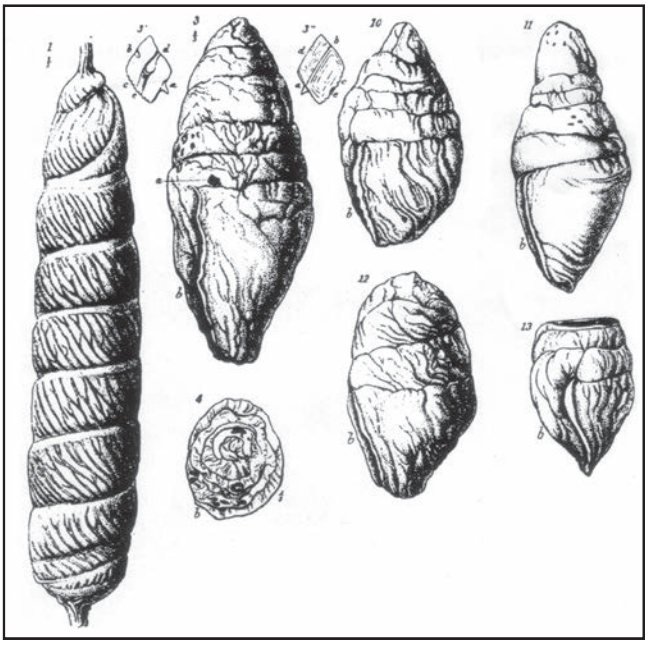

***Figure 2**. Drawings of coprolites (from Buckland, 1836).*

have come from the Carboniferous Wardie Shales (Oil Shales Group) near Edinburgh: however, it is not known who made the table or when (Sharpe, 2004). A pair of coprolite ear-rings are said to have been made for his wife but it is not known if they survive today.

Coprolitology led to the appearance of several scurrilous cartoons, including one by Henry De La Beche (first Director of the Geological Survey) entitled “A Coprolitic Vision”, which showed a figure in academic gown and mortar board, presumably Buckland, in a cave with large coprolite-shaped stalagmites and several animals in the act of making more coprolites (Fig. 4). Even the academic has a dark shadow on the ground between his legs!

Thus, thanks to Buckland, coprolites were confirmed as including the fossilized remains of animals’ excreta. Later they were often referred to as dinosaur dung, though only a few bear the appropriate reptilian spiral shape with pointed ends, and the nature of dinosaurs was not recognized until Richard Owen coined the name more than ten years later. Some nodules are just irregular lumps of phosphatic material. Purists might wish to use terms such as pseudo-coprolites or false coprolites for any nodules which cannot be shown to be excretions, but the term coprolite has long been used commercially to embrace any phosphatic nodules, whether excreta or not. Scientifically it is probably best if they are all referred to as phosphatic nodules, though coprolite is normally taken as a colloquial or commercial equivalent term.

***Figure 3**. Table of coprolites (and septarian nodules) made for Professor Buckland (photo: Lyme Regis Philpot Museum).*

The Origin of Coprolites

It seems likely that most coprolites came from the larger marine reptiles or fish, which fed on their smaller brethren and concentrated phosphate in their faeces. Though most of the beds with coprolitic nodules were marine, remains of terrestrial reptiles preserved in the phosphatic nodules can represent carcasses washed in from rivers draining nearby land areas and scavenged by both marine reptiles and fish. Nodules were also recycled by erosion from earlier strata such as the Kimmeridge Clay of late Jurassic age, re-deposited in Cretaceous sediments.

Phosphatic nodules are not uncommon in most of the thick mudstone formations of the British Mesozoic and Cenozoic, ranging from the Lias to the London Clay; however, they are usually too widely dispersed to form an economic resource. The nodules appear to have formed at or just below the sea-bed during early diagenesis. Soon after their formation, winnowing out of the surrounding clay particles by strong currents and tides during periods of slight uplift above wave-base served to concentrate the nodules in lag gravels, many of which therefore mark non-sequences or disconformities. These lag gravels form the commercially exploitable coprolite beds. Repeated winnowings at successive horizons occasionally led to several nodule bands lying sufficiently close together to be exploited as single units. Regrettably, due to the commercial exploitation, there are few sections through the relevant strata available today meaning that a complete sedimentary and palaeontological analysis would be difficult.

***Figure 4**. The cartoon by Henry De La Beche.*

In Mesozoic coprolite beds, the fossilized marine reptiles recorded include ichthyosaurs, plesiosaurs and pliosaurs. Amongst the terrestrial reptile genera recorded are *Craterosaurus, Dinotosaurus, Megalosaurus* and *Iguanodon*. The scattered records include both Jurassic and Cretaceous reptiles. Mesozoic crocodiles, turtles, sharks, and a variety of shells, particularly ammonites, belemnites and other molluscs have also been found. It is likely that the calcareous shells were replaced by phosphate after death and burial (McKerrow, 1978).

Professor John Henslow (Charles Darwin's mentor), his assistant Seeley and their students visited the active mid 19th century coprolite diggings around Cambridge and amassed a collection now housed in the Sedgwick Museum, Downing Street, Cambridge. A small selection is on display. A thorough search of Victorian geological literature and of museum records could extend the list of genera found though some identifications are probably rather loose and the locality records were often rather vague at that time, as the Victorian palaeontologists wished to keep their sources secret.

In addition to Cretaceous coprolites, numerous bones of Pleistocene mammals were recovered from the overburden on some of the coprolite pits and were added to the mixture. Neither coprolite diggers nor palaeontologists made much attempt to differentiate Cretaceous from Pleistocene finds. Though they were still bone and less soluble, they contributed to fertilizing properties over a longer period. The Pleistocene mammals included mammoth, rhinoceros, hippopotamus, deer, pig, hyena, oxen and horse. In Suffolk there were scattered finds of early Pleistocene mammal bones as well as teeth from the sharks *Carcharadon* and *Lamna* and there were occasional records of whale ear bones.

The early Pleistocene Crags of Suffolk and Essex were an important source of coprolites, mainly mammal bones concentrated at the base of the Red Crag. In 1866 Woodward noted a large accumulation at Sutton, amounting to some 220 tons, collected over the area north of Felixstowe. Gravelly lag deposits with local concentrations of phosphatic nodules marking winnowing events have been found in Tertiary clays of the southern North Sea (Balson, 1987).

P_2O_5	26.75	25.29	27.01
CaO	43.21	45.39	46.60
Insoluble siliceous matter	8.64	6.22	6.04
Al_2O_3	1.36	2.57	1.41
Fe_2O_3	2.46	1.87	2.08
MgO	1.12	0.48	1.06
Na_2O	0.50	0.73	n.d.
K_2O	0.32	0.84	n.d.
Moisture & organic matter	4.63	4.01	3.52
CO_2	6.66	5.13	5.49
SO_3	0.76	1.06	n.d.
F and loss	4.96	4.95	6.79

Analyses (%) of three nodules (from Voelcker, 1860).

Composition

The coprolite nodules are black, grey, brown or yellow lumps of impure calcium phosphate with the largest weighing over a kilogram. The mineral composition was investigated in the 19th century and is mainly carbonate-apatite ($Ca_5(PO_4,CO_3)_3F$), in which the carbonate ion replaces at least some of the fluorine ions present in apatite. This is sometimes known as phosphorite, though that term is better restricted for any commercial material containing phosphorus. The fossil bones were originally phosphate in the form of hydroxyl-apatite. The enclosing concretionary material, mainly calcium carbonate, was derived by nucleation from the surrounding sea-water.

The variation between nodules is attributable to the varied amounts of indigestible remains of fish etc. Commercial analyses usually express the phosphate content as a percentage of P_2O_5 which is generally around 25% in the nodules. Analytical records of various alleged phosphate minerals have included dahllite, francolite and floridite, all of which are now discredited as definable minerals (see also Dana, 1898).

Phosphate rocks have been produced at several localities in the Lower Palaeozoic rocks in Wales but none of these appears to be coprolite and of course the large reptiles had not appeared then. A comprehensive survey and list of analyses of both British and foreign phosphate deposits was prepared by Notholt & Highley (1979). Analyses of coprolites from the Speeton Clay of east Yorkshire were provided by Scott et al. (1987). Comparable analyses of a large dinosaur coprolite from the Cretaceous of Saskatchewan, Canada, have been given by Chin et al. (1998). Phosphate is sometimes associated with uranium in other contexts but no reference to uraniferous coprolites has been located.

Sources

Though bony fossils and nodules found at the base of the Red Crag in the cliffs at Felixstowe were ground up and used as fertilizer in Suffolk and Essex in the late 1820s, the chemical manure industry did not blossom until Lawes' patent in 1846. John Bennett Lawes apparently bought his patent from Sir John Murray who had introduced chemical manure in Belfast (later Dublin) in 1817 by treating bone meal with sulphuric acid and he took out a Scottish patent in 1842. Murray also gave lecture courses on the benefits of chemical manures in both Belfast and Dublin. Lawes bought Murray's patent in 1846 and established his first factory at Deptford in London but later moved to Neptune Quay in Ipswich, where much of the product was shipped out via the River Orwell. In 1843 Lawes inherited his father's estate at Rothamsted where he experimented with fertilizers and founded the Agricultural Research Institute which survives to this day.

Treatment of the phosphatic nodules with sulphuric acid produced what Lawes dubbed "superphosphate", effectively a mixture of calcium mono-, di-, or tri-

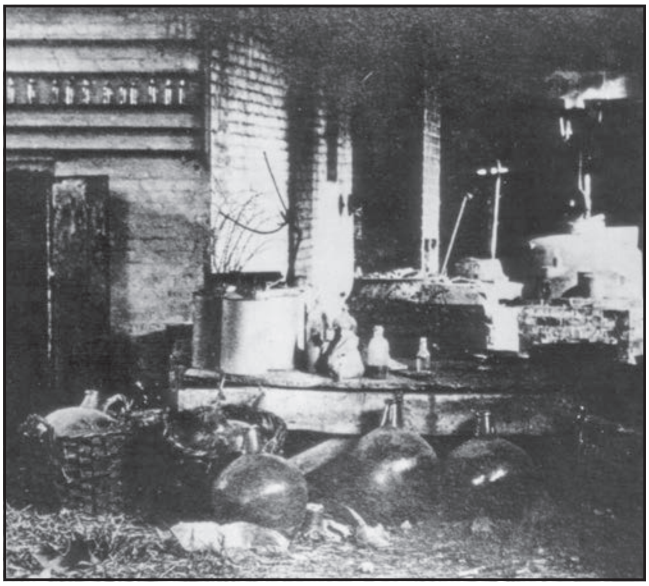

Figure 5*. Inside the Lawes' Chemical Manure factory at Rothamsted, where superphosphate was first made (photo: Institute of Agricultural History and Museum of Rural Life, University of Reading).*

hydro-phosphate and calcium sulphate, much more soluble and thus more accessible to growing plants. A by-product was an awful smell, mostly hydrogen sulphide, which soon forced the removal of the works to a countryside locality on the River Orwell at Bramford outside Ipswich.

The German chemist Justus von Liebig is also credited with having discovered the fertilizing properties of phosphate rock treated with sulphuric acid about 1840; it is therefore a moot point as who should be credited with the first discovery, whether it was Murray, Lawes or Liebig..

Later the focus of the industry moved to Cambridgeshire following Professor Henslow's remarks to the British Association for the Advancement of Science when it met in Cambridge in 1846. He drew attention to the coprolite nodules in various Cretaceous strata near that town. The earliest recorded exploitation of coprolite beds in Cambridgeshire was in 1848 when John Ball opened pits at Burwell, near Newmarket; he used a windmill to grind the nodules. This was only two years after Henslow's report and within another year or so several other coprolite pits were opened near Cambridge. The coprolite diggers also put choice nodules with fossils on one side for lucrative sale to both professors and students at the Geology Department of the University of Cambridge, and some were offered for sale on market stalls. The nodule distribution was noted as being in a belt of country rarely more than 8 km wide along the foot of the Chalk escarpment from Cambridgeshire into Bedfordshire, Buckinghamshire and Oxfordshire, roughly the outcrop of the Gault and Greensand Formations. Though these are marine strata, they also contain fossils of terrestrial animals, which are thought to have been washed in by rivers draining the London land-mass.

Stratigraphic Distribution

The stratigraphic horizons with phosphatic nodules include the base of the Woburn Sands (Lower Cretaceous) around Great and Little Brickhill, Buckinghamshire, and around Ridgmont and Potton in Bedfordshire, where the Potton Nodule Bed was an important phosphate source. The so-called Junction Beds yielded coprolites at the base of the Gault near Leighton Buzzard, and the Shenley Hill Limestone was a calcite-cemented nodule bed overlying the equivalent Silver Sands near Leighton Buzzard. The base of the Upper Gault had coprolite beds at several localities between Towersay, near Thame, Oxfordshire, and Slapton, Buckinghamshire, and the basal Gault around Sandy, Bedfordshire, was an important horizon. Nodules have occasionally been worked at the base of the Gault near Folkestone, Kent, and Farnham, Surrey. The Cambridge Greensand, a sandy facies of the Upper Gault, which marked a non-sequence at the base of the Chalk Marl, was particularly rich in nodules and became an important horizon for exploitation.

These coprolite-bearing formations crop out along a tract 80 km long from Harlington, east Bedfordshire, to Soham, Burwell, Swaffham and Upware in Cambridgeshire (Fig. 6). Indeed some two dozen separate pits were opened around Cambridge. Coprolites were also obtained from equivalent strata near West Dereham and Crimplesham in Norfolk and from the Lower Cretaceous Speeton Clay on the

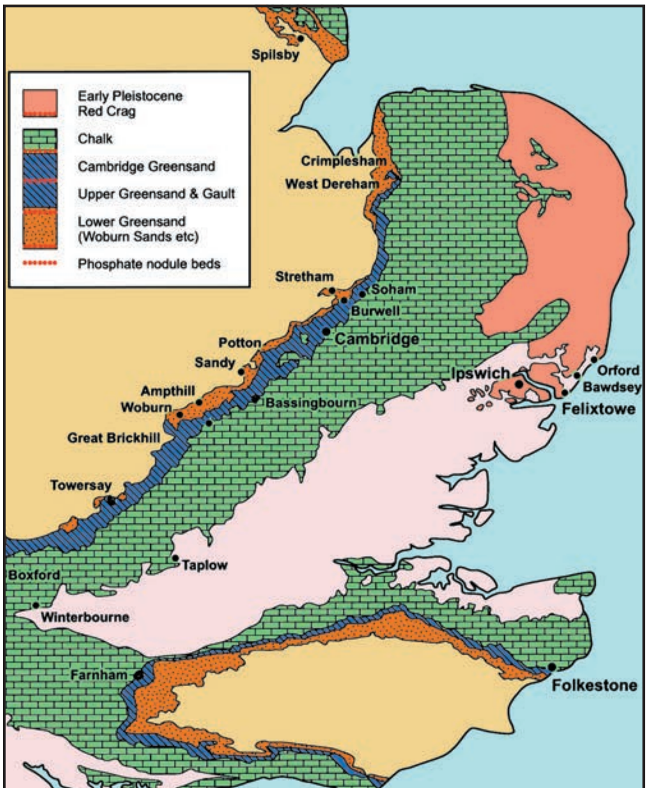

Figure 6*. The main outcrops of the coprolite-bearing beds within the Lower Greensand, Gault and Red Crag series.*

Yorkshire coast, where winnowed horizons can be found on the foreshore; underground mining was attempted at Speeton without much success. A little underground mining was also tried at Bassingbourn in Cambridgeshire but flooding problems soon caused abandonment. A few nodules were obtained from the late Cretaceous Carstone of Norfolk and Lincolnshire. Phosphate rock at the base of the Spilsby Sandstone (Portlandian) in Lincolnshire was investigated during World War II but no production ensued. Some production was obtained from the Cambridge Greensand around Trumpington and Grantchester, Cambridge, during World War I and other localities at this horizon were investigated but were considered uneconomic.

"Hard grounds" representing brief emergence episodes in the Chalk show local concentrations of phosphate but none have proved profitable to any extent in England, in contrast with France and Belgium. Phosphatic Chalk was investigated near Taplow, Bucks., during both World Wars. Other Chalk localities investigated included Boxford and Winterbourne in Berkshire. The Glauconitic Marl of the Isle of Wight was also tested. Nodules have also been recorded in the Jurassic strata at Brora in northeast Scotland, and in the Upper Cretaceous Greensand of Morven in the western Highlands and in Antrim in Northern Ireland.

Most of the Cretaceous formations that contain the phosphates are fairly thin across the margins of the London land mass, and winnowing concentrated nodules in beds usually less than half a metre thick at or near the base of each unit. Occasionally nodules were concentrated in sea-bed hollows. Some winnowing of the underlying late Jurassic Kimmeridge Clay also occurred and thus Jurassic reptile bones were found in Cretaceous nodule beds.

Bones and fragments, mainly mammal, some enclosed in phosphatic nodules, are well-known in the early Pleistocene strata of east Suffolk, particularly the base of the Red Crag along the Deben and Orwell valleys and in the cliffs near Felixstowe. The nodule bed was worked at several localities on either side of these estuaries, particularly at Sutton, Butley and Waldringfield. There was even concern that the Red Crag might be totally removed as a geological formation (Charlesworth, 1868). Coprolite pits and works are scattered on the early Ordnance Survey maps but little can be seen today. In most of these occurrences the Red Crag lies on the Eocene London Clay and some of the fossils or nodules were winnowed out of the latter to be concentrated at the unconformity. Similar but small concentrations of nodules can be still found in the well-known exposures of the Red Crag at Bawdsey Cliff, north of Felixstowe, and at Walton-on-the-Naze, in Essex. Though the nodules are not common today they were sufficiently abundant in 1866 to yield a stockpile of 220 tons at Sutton. A similar lag gravel was also found at the base of the Coralline Crag at Sudbourn, near Orford, but this formation has only a limited extent and it seems that only one pit was worked there.

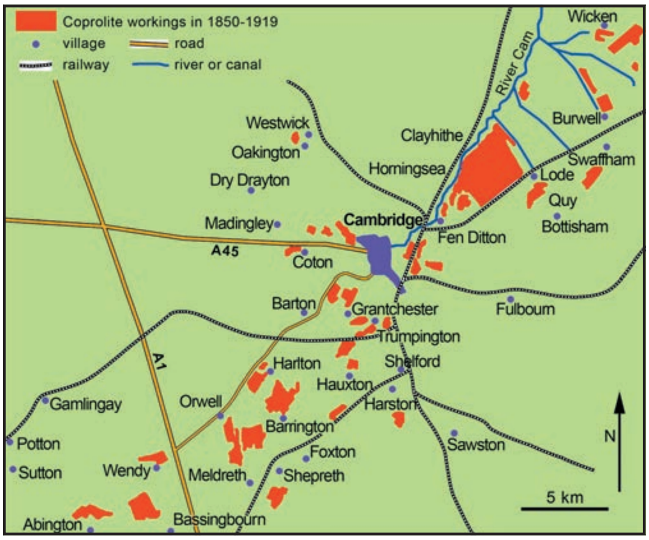

Figure 7. *Coprolite workings around Cambridge (after map by Sedgwick Museum).*

Phosphatic nodules occur on hard grounds in most of the Jurassic ironstones with phosphate content being around 1%. Mass production methods of ironstone working did not separate the nodules and the Northampton Sand, Marlstone, Frodingham and Cleveland Ironstones yielded iron and steel where the phosphorus content was undesirably high. Some of it was removed in basic slag, which was sometimes ground up and sold as fertilizer.

Though phosphatic nodules also occur in several other stratigraphic formations, such as the Lower Lias of Dorset and Gloucestershire, the Middle Lias of East Leicestershire, and the London Clay of Hertfordshire, there seems to have been no attempt to work them.

Extraction

Prospecting for phosphatic nodules was by observing the occasional sample thrown up by ploughing and in marl pits. Cliffs along the coast and rivers revealed more nodules. Sufficient nodules led to pits being excavated in appropriate fields. Later a hand-operated

Figure 8. *Coprolite diggings at Trumpington, Cambridge, during World War I, with an early dragline in the background (photo: Cambridgeshire Collections).*

Figure 9. *Digging for coprolites at Great Brickhill (photo: Buckinghamshire County Museum).*

corkscrew borer was used to test for the abundance of coprolites. Once located, coprolite production was by open-cast methods and whole fields were torn up. A few unsuccessful attempts were made to follow seams by underground mining. The removal of up to 8 metres or so of overburden uncovered coprolite nodule beds up to around half a metre thick. Up to 2000 tons per acre have been claimed, though around 250 tons per acre was usual, making the land much more profitable than agriculture. Up to 500 tons per annum were recorded at Speeton (Scott *et al*. 1987). Coprolite digging was a labour-intensive industry with thousands being employed and barracks to house workers were sometimes erected. During World War I extraction became mechanized and early draglines were used at Trumpington near Cambridge. Most of the works were operated by men but women were occasionally employed in washing procedures, e.g. at Potton. Coprolite-mining communities sprang up and became the focus of secondary trades with catering establishments, public houses and chapels being opened nearby. Ancillary trades such as carpenters, blacksmiths and engineers also developed around the workings.

Once raised, the nodules were processed to remove unwanted clay and sand by washing either in a trough or in a cylindrical wash-mill using water from wells or drawn from a nearby river. Surplus clay and sand were returned to worked-out diggings and fields; though very muddy the latter were returned to agriculture perhaps slightly lower in altitude. Nodules were usually carried to a processing plant at a nearby locality using carts (locally known as tumbrils). Temporary tram roads had trucks running on L-shaped rails drawn along by horses or, later, by steam engines (Fig. 10).

As output grew, barges on rivers and canals were used until railways reached the area in the 1860s onwards. Centralization grew with a few mills crushing and grinding the nodules in preparation for acid treatment. Some bulk transport went by sea and there is still a Coprolite Street by Neptune Quay at Ipswich. Nodules were also shipped to Barking for processing there. In the last years of the industry it became mechanized and early draglines and steam shovels were used to remove the overburden and both light railways and lorries were used for transport.

Figure 10. *An early steam railway used for transporting coprolites; Whaddon, near Meldreth, Cambridgeshire (photo: Mrs Coningsby, Whaddon).*

Figure 11. *Transporting coprolites by tumbril to Millbrook Station, Bedfordshire (from an old postcard).*

Utilization

Following the Industrial Revolution the need to feed the growing work-forces in the cities necessitated improvements in agricultural production in the early 19th century. Land-owners soon appreciated that the addition of bone meal improved crop yields and it was not long before it was realized that phosphate was the critical factor. However, bone meal only dissolves slowly in soil water and in 1842 John Bennett Lawes, a Hertfordshire landowner, discovered that ground-up phosphatic nodules from the Red Crag and other strata near Felixstowe were much more soluble if sulphuric acid was added. Suffolk manure merchants such as William Colchester, Edward Packard and Joseph Fison became interested and followed Lawes' lead in collecting nodules from the Red Crag. Lawes patented his discovery as "superphosphate" and works were set up in Ipswich and on his estate at Rothamsted; another superphosphate works was operated by Lawes on Thames-side docks at Barking. Colchester, Packard, Fison and the Prentice Brothers had fertilizer works in Ipswich but later moved to near Bramford and Stowmarket further up the Orwell valley. Transport was by lighters on the river. Joseph Fison later merged his company with the others and built up today's Fison's agricultural chemicals industry with a base at Levington, down river from Ipswich. There is still a short Coprolite Street in Ipswich: the site of the works was later used by Ransome's lawnmower factory but it is now occupied by an apartment block. Several coprolite mills were set up in and around Cambridge and some of that city's stylish Victorian buildings were built out of the profits.

Coprolite contractors paid landowners up to £200 per acre for the right to raise the nodules which they sold for up to £3.75 per ton. At a yield of 250 tons per acre this gave them a good profit margin particularly as labour costs were low. Statistics of coprolite production are incomplete, but a total of about 1.2 million tons was raised between 1874 and 1909. A reasonable estimate of the pre-1874 yield is around 737,000 tons, making an overall total of two million tons. Of this about 325,000 tons came from Suffolk, mainly from the Red Crag. Production expanded across the southeast Midlands counties in the 1850s and 1860s and peaked in the 1870s, when 258,150 tons of coprolites were recorded in 1876. Thereafter production fell rapidly to a maximum of 30,000 tons per annum in the 1880s. The last pit near Cambridge was at Burwell, worked intermittently until 1919. Only 4 tons were recorded in 1909 but there was a temporary resurgence of production at Trumpington, near Cambridge, during World War I when imports were restricted: prisoner of war and Irish republican labour were used. The decline was a result of exhaustion of the accessible nodule seams and increasing depth of overburden to be removed. The islands off Peru had largely been stripped of guano by the 1870s and there was increasing competition from imports of rock phosphate. At the same time, demand fell owing to cheap foodstuffs being imported from Argentina and Australia etc. Investigations of the possible utilization of phosphatic chalk during World War II came to nothing.

Much of the phosphate used in Britain today, over a million tonnes per annum, is imported from late Cretaceous to Eocene rock phosphate strata in north and west Africa, particularly Morocco and Senegal; lesser amounts come from Tunisia, Egypt, Jordan, Israel and Mauritania. Phosphatic guano deposits have been dug from several Pacific Islands, such as Nauru, leaving a bare karst landscape.

In spite of what must have been an intensive industry in Victorian times, with large tracts of land being torn up, there is little to show for it today, except for collections in the Sedgwick and other museums. There is little archaeological evidence to be found. A few flooded trenches can still be found near Quy Fen, east of Cambridge. Most pits have been back-filled and some have been built over. One cannot help wondering how many fossil species were lost to science by being ground up for use as fertilizer.

Figure 12. *Coprolite Street, Ipswich, today (photo: Chris Duffin).*

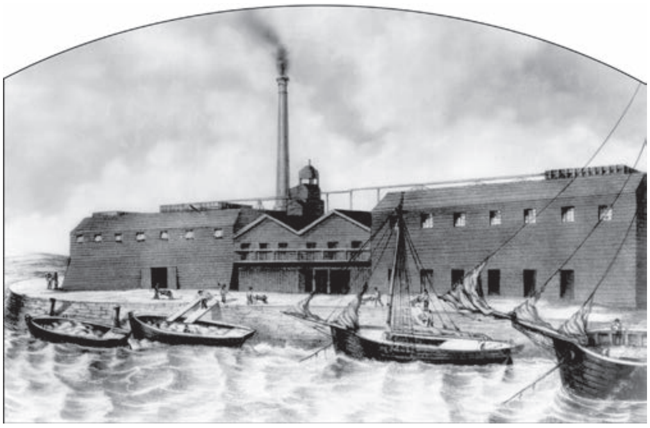

***Figure 13**. Lawes Chemical Manure works on the River Thames at Barking (photo: Valence House Museum).*

Acknowledgements

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"Records of warfare…embalmed in the everlasting hills": a History of Early Coprolite Research

Christopher J. Duffin

Abstract: Although 'coprolite' was introduced as a term for fossil faeces by William Buckland in 1829, specimens had been described and figured in earlier literature. John Woodward described specimens from the Chalk as fossil larch cones a century before Buckland's work, an identity later confirmed by James Parkinson in 1804. Gideon Mantell described more Chalk specimens in 1822, whilst François-Xavier de Burtin described further spiral forms from the Brussels area as fossil nuts. Buckland first identified fossil hyaena faeces from the Ipswichian cave deposits of Kirkdale in Yorkshire, and then applied his experience to specimens from the Jurassic of Lyme Regis and the Rhaetic Bone Bed of the Severn estuary area. He developed a nomenclature for the specimens that he described, the first such attempt in ichnology. A rich network of domestic and foreign colleagues and correspondents either supplied him with information and further specimens, or applied his conclusions to their own material. Buckland's coprolite research engendered good-natured ribaldry from his colleagues.

The first half of the nineteenth century was a time of radical change in thinking amongst the natural sciences in general, and in geology in particular. A cutting edge contributor to this rapid pace of conceptual change was William Buckland who worked tirelessly as a politician for science, gave many a helping hand to up and coming colleagues, developed a rich network of contacts and friends, and acted as a popular figurehead for geology. Among the many innovations for which he was at least partly responsible was the growing appreciation that the fossil record sampled a diversity of once living communities, rather than being the chaotic record of a universal deluge. It was Buckland who first recognized that in the same rocks that sported the panoply of body fossil such as shells, teeth and bones, there were also traces of the daily activities of once living organisms – footprints and faeces (Duffin, 2006). Coprolites were first identified by William Buckland, who also gave us the name, effectively making him a founder of palaeoichnology.

Earliest Discoveries

John Woodward (1665-1728), was apprenticed to a draper at age 16, and worked in London (Fig. 1). He rose to become Professor of Physic at Gresham College in London, but had wide natural history and antiquarian interests. After collecting his first fossil from the London Clay in 1688, he developed a passion that involved a large and historically important collection, which he bequeathed to Cambridge University. He also endowed the famous Woodwardian professorship at what is now the Sedgwick Museum, partly so that his specimens could be cared for in the future.

Woodward set forth his views that the fossils which he had collected were once living creatures which had been destroyed by the Deluge in his *Essay toward a Natural History of the Earth* (1695), although the details of his thesis brought him much controversy and protracted acrimonious exchanges with other natural historians of the day. The handwritten manuscript cataloguing his collection was published posthumously as *An Attempt towards a Natural History of England* (1728-9). Within his Classis II, Pars IV, "Nuts and other like fruits found in the earth", he gives brief notice (1729 p22) of: *b. 72. Three cones seeming to be of the Larix. From Cherry-Hinton Chalk pits near Cambridge. These were not come to ripeness or maturity*.

Woodward was anxious to get as much information from these and similar specimens as possible. By comparing fossils in the preceding entry with extant larch cones, Woodward concluded that one of his specimens may have represented the growth stage normally reached in May.

Specimens from the same pits in the Middle Chalk at Cherry Hinton near Cambridge were later illustrated by James Parkinson (1755-1824), the physician famous for his treatise (1817) on the 'Shaking Palsy', later named 'Parkinson's Disease' in his honour. He published *Organic Remains of the Former World* using an epistolary approach to his consideration of fossils in 1804. Letter XLVII considers various aspects of plant fossils, and Parkinson echoes Woodward's comments

Figure 1. *Portrait of John Woodward (1665-1728) (photo: David Ward; Sedgwick Museum).*

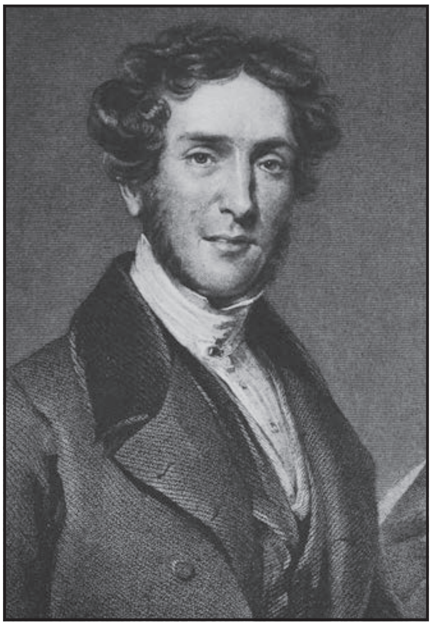

Figure 2. Gideon Mantell's portrait, 1790-1852 (from Woodward, 1908).

that the Cretaceous specimens "approach very near in resemblance to the juli of the larch tree". He adds the comment that a Dr Parsons considers them to be root structures rather than cones, but concludes that they are "either aments [catkins], or cones, of some tree not now known, at least to the European botanist" (Parkinson 1804, p456). The Dr Parsons in question is probably James Parsons (1705-1770; Chalmers 1815), physician and antiquary who had a passion for fossils and described fossil fruits from the London Clay of Sheppey. Parkinson did express concern that the Chalk specimens were not associated with any other plant remains (Parkinson, 1804 Plate VI, figs. 15, 17).

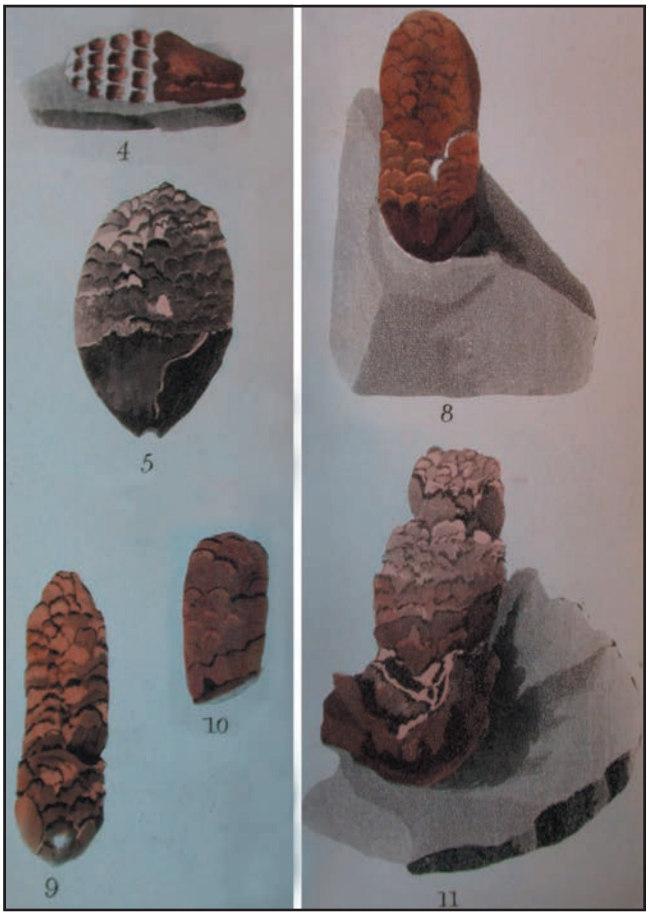

Figure 3. Coprolites from the Chalk at Hamsey (from Mantell, 1822).

Gideon Mantell (1790-1852) described and illustrated specimens of similar morphology from the Chalk at Hamsey, near Lewes, his home town, in Sussex (Fig. 3). Commenting that "their nature is still involved in obscurity", he remarks that they have "excited considerable attention", and discussion centred around whether they were plant or animal in origin (Mantell, 1822). Correspondence with John Hailstone, Woodwardian Professor at Cambridge from 1788 to 1818, elicited the opinion that Woodward's specimens had a "vegetable origin beyond all doubt" (Mantell, 1827), partly since he had described coniferous plant remains from the same quarries (Hailstone, 1816).

Mantell gives the most extensive description of these specimens, of which he claimed to have been given 50 or more by his brother, noting that they measure up to 5 cm long, have a scaly, corrugated surface, cylindrical shape and tapering obtusely to a point at one end. He makes the comment that they appear to have the same composition as associated vertebrate remains, and that some have fish scales attached to them. In comparing his specimens with larch cones, Mantell (1822) correctly indicates that the items from the Chalk have a spiral form, rather than possessing individual, imbricated scales. He goes on to describe and figure further specimens, also tentatively compared to larch cones, from the Chalk at Steyning, and repeating some of the elements of his discussion, eventually coming to the conclusion, "that they may hereafter prove to be parts of fishes".

François-Xavier de Burtin (1743-1818) also postulated a botanical origin for local coprolites which he described and figured in his 1784 *Oryctographie de Bruxelles* (Fig. 4). Having spent some time discussing certain specimens which he concluded were comparable to coconuts, Burtin (1784) turned his attention to an elongate, spindle-shaped structure possessing 6 evenly-spaced spiral turns. He makes the interesting comment that he would have had no hesitation in classifying the specimen as an unknown coral ("polypières"), were it not for his earlier discussion on coconuts. In spite of the fact that he says he could find no evidence of internal cellular structure or points of attachment to twigs, he concludes that it must be an unknown fruit or kernel – at least it was very different from any other fruits or nuts that he either possessed or had seen elsewhere.

Kirkdale Cave

William Buckland was born the eldest son of the Rev. Charles Buckland on 12th March 1784 at Axminster in Devon (Rupke, 1983; Duffin, 2006). In 1813, Buckland was appointed Reader in Mineralogy and then Reader in Geology in 1818.

Figure 4. *Coprolites from near Brussels (from de Burtin, 1784).*

Quickly establishing himself as a popular lecturer, he illustrated his talks with the liberal use of specimens, maps and sections, holding the audience not only with the innovative approach and scientific content of his lectures, but also his rather theatrical style and sense of humour. Completing something of a 'Grand Tour' of European geology in the company of W.D. Conybeare and G.B. Greenough, he spent some time with August Goldfuss who was engaged with the careful excavation of the bone-bearing sediments in the cave floor at Gailenreuth near Muggendorf in German Franconia.

"Little did the boy think, who stepped amongst the bushes, with which the mouth of the Cave was overgrown; or the woodman, when felling the oak; that he was walking on a spot, which in some future time, would interest the literary world, and draw many from the smoke of populous and polished cities and towns, and from the retired cloisters of colleges, to explore a Cavern, then unknown, and to visit a situation, which before had been comparatively unobserved! But unexpected circumstances every day unfold some mysteries, and give fresh stimulus to the energies of the human mind." (Eastmead, 1824 p4).

His experience in Germany was to hold Buckland in good stead when he later examined cave deposits at first hand in Yorkshire – deposits that would, indeed, "give fresh stimulus to the energies" of his mind! Quarrying of oolitic limestone was taking place near the small village of Kirkdale, a few miles away from Kirby Moorside in Yorkshire. During the summer of 1821, John Gibson (George, 1998), a manufacturing chemist, was visiting friends in the area. He noticed large blocks of limestone being used to repair the roads; scattered between them were various pieces of bone and tusk. Gibson traced the origin of the material to the small quarry by the side of Hodge Beck (SE678856), adjacent to Kirkdale Church. Believing the remains to have come from modern cattle which had either succumbed to the disease 'murrain' (probably Rinderpest), a highly infectious viral cattle plague, or had fallen into an open chasm, the quarrymen had scattered them as aggregate on the local roads. The land owners (the Welburn Estate and a local solicitor) generously gave permission for the cave contents to be fully excavated, hoping that the bones and teeth would, "fall into the hands of such persons, who would deposit them in public institutions or otherwise take care of them, to preserve the interesting memorials of this wonderful cavern" (Eastmead, 1824 p7). Keen amateur geologists, collectors and enthusiasts were happy to oblige and gathered up some of the material; local surgeon, coroner and apothecary, Thomas Harrison also discovered the cave in the autumn of 1821 (*Gentleman's Magazine*, February 1822), while George Young and his co-worker John Bird, and Rev. William Eastmead an independent minister in the village, all collected from the site. Retired colonel William Salmond reputedly funded and superintended the excavation, and executed the plan drawing of the cavern used in subsequent publications. On December 7th 1822 Salmond met with his colleagues Anthony Thorpe and James Atkinson, a retired surgeon, in an attempt to bring their various collections of Kirkdale fossils together in a suitable repository; hence the Yorkshire Philosophical Society was born. Gibson was credited with completing the bulk of the excavation and accumulating a huge collection which was shown, among others, to James Parkinson. Other material found its way into a wide range of personal collections and public institutions.

It was Edward Legge, Bishop of Oxford, who eventually informed Buckland about the discoveries at Kirkdale. Joseph Pentland was told of the finds. The Irishman was working in the laboratory of Georges

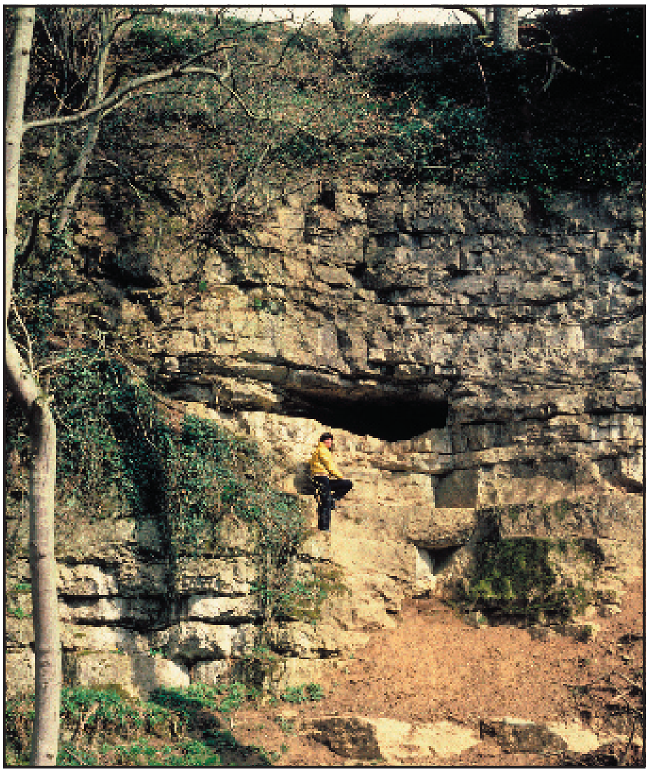

Figure 5. *Entrance to Kirkdale Cave today.*

Figure 6. *Dabié Cave, Jordan (photo: Stephan Kempe).*

Cuvier, Parisian father of comparative anatomy who, at that time, was engaged in writing the second edition of his *Recherches sur les ossemens fossiles*. William Clift, curator of the John Hunter Collection at the Royal College of Surgeons, had also written to Cuvier, sending him some drawings of the better material from Kirkdale. Pentland wrote to Buckland on 26 November 1821, urging him to procure some specimens from Kirkdale for the French Professor. Buckland accordingly visited the cave in December 1821, and joined the team. At around 75m long, 4m high and up to 2m wide (Fig. 5), this cave was smaller and contained thinner deposits than those he had seen during his visit to Germany. Buckland's excited descriptions of the cave to his correspondents refer to a profusion of the comminuted, trampled bones and teeth of hyaenas, mixed together with a host of other species, including "Elephant, Rhinoceros, Hippopotamus, Horse, Ox, Deer, Fox and Water Rat", forming a sort of pavement over the cave floor. A full faunal list is given by Boylan (1981). Buckland went on to conclude that the assemblage represented a hyaena den, analysing breakage patterns of the bones to prove that they were from carcasses dragged into the cave and broken by feeding action. In doing so, he was the first person to conduct anything like a rigorous study of biostratinomy.

Figure 7. *Painting by R. Ansdell R.A., from about 1843, of William Buckland dressed for fieldwork in a tailed topcoat over a dark waistcoat and white shirt, with a top hat, umbrella and black gloves, and brandishing a blue serge collecting bag.*

Buckland was impressed by the fact that bone debris was strewn all over the cave floor, including the deepest recesses of the cavern, and that the walls and bone fragments had been polished by the passage of the predators through the cave. His ecological explanation of the fauna as a hyaena den was not universally accepted; there was some tension between Buckland and George Young, for example. Young preferred the notion that the accumulation of bones was part of a diluvial (flood) deposit and left the excavations as a result of the difference of views.

Many did embrace Buckland's view, however, and relished the idea of antediluvian hyaenas roaming the Yorkshire countryside in search of prey. Similar hyaena dens have been described much more recently from the volcanic plateau of Al-Shaam Harrat in Jordan (Kempe et al., 2006). The Dabié Cave (Fig. 6), with its almost unbroken covering of bone scatter, gives an impression of the sight, albeit partially obscured by marly sediment and stalagmite, that must have met Buckland's eyes as he entered and excavated Kirkdale cavern (Fig. 8).

Nestling between the bones and teeth, much as on the floor of Al-Fahda Cave (also in Jordan, Fig. 9), Buckland noticed some small balls of a white material. Intrigued as to their nature and origin, he wondered if they might be fossilised faeces deposited by the hyaena (Fig. 10). He referred to them both in his letters and in print as *Album Graecum*, an old apothecarial term pertaining to dog faeces which demonstrate the property of turning white on exposure to air. Rather frighteningly, *Album Graecum* (also known as Stercus Canis Officinale) was used as an ingredient, particularly in the 16th and 17th centuries, in the treatment of colic, dysentery, scrofula, ulcers (Wootton, 1910) and especially quinsy (a peritonsillar abscess that can form as a complication of acute tonsillitis), both as a component of a poultice or plaister and (possibly worse!) a gargle. The 'drug' was obtained by feeding otherwise half starved dogs with bone fragments; the protein inside was digested and absorbed from the bone, leaving an easily blanched

Figure 8. *Caricature by W.D. Conybeare, of Buckland entering the Kirkdale hyaena den, only to find it occupied.*

***Figure 9**. Hyaena coprolite in situ in Al-Fahda Cave, Jordan (photo: Stephan Kempe).*

phosphate-rich faecal pellet which was collected with some eagerness (Burnett, 1833). The parallel drawn by Buckland between *Album Graecum* and hyaena coprolites thus becomes both appropriate and striking.

Buckland described the Kirkdale material (Buckland, 1824 p20) as having an external form that *"is that of a sphere, irregularly compressed, as in the faeces of sheep, and varying from half an inch to an inch and a half in diameter; its colour is yellowish white, its fracture is usually earthy and compact, resembling steatite, and sometimes granular; when compact, it is interspersed with small cellular cavities, and in some of the balls there are undigested minute fragments of the enamel of teeth."* Anxious to confirm his suggested interpretation, he sent some of the material to William Hyde Wollaston, the chemist, physicist and mineralogist. Wollaston showed the specimens to the Menagerie Keeper at the Exeter Exchange, who immediately noted their similarity to the droppings produced by the Spotted Hyaena (*Crocuta crocuta*). The analysis conducted by Wollaston "finds it [the hyaena coprolite] to be composed of the ingredients that might be expected in faecal matter derived from bones" (Buckland, 1824 p22). In his reply to Buckland, Wollaston (24 June 1822; Buckland Papers, Royal Society) wrote that "though such matters may be instructive and therefore to a certain degree interesting, it may as well for you and me not to have the reputation of too frequently and too minutely examining faecal products."

Buckland's study of Kirkdale and its fauna was initially published in the *Philosophical Transactions of the Royal Society* in 1822, and then issued as the *Reliquiae Diluvianae*, published by John Murray in 1823. The importance of the work was recognised by the Royal Society, who awarded Buckland the prestigious Copley Medal for 1822, an honour reserved for "outstanding achievements in research in any branch of science". Buckland's was the 62nd in a long sequence whose pedigree included men such as Benjamin Franklin, William Herschel, Joseph Priestley, James Cook and William Wollaston himself, and was the first such award for geology. The then President of the society, Humphrey Davey, commented, "I do not recollect a paper read at the Royal Society which has created so much interest as yours" (letter dated 18 March 1822; Buckland Papers, Royal Society).

Shortly afterwards (1827) Buckland published a note in the *Proceedings of the Geological Society of London* of his lecture of November 17 1826 entitled "*Observations on the bones of hyaenas and other animals on the cavern of Lunel near Montpelier, and in the adjacent strata of marine formation*". Rather larger than Kirkdale, this cave contained a similar fauna to that of Yorkshire, but Buckland was astounded by the high incidence of hyaena faeces – "an extraordinary abundance of the balls of *album graecum* in the highest state of preservation". He concluded that, at Kirkdale, "a large proportion of the faecal balls of the hyaenas appear to have been trod upon and crushed at the bottom of a wet and narrow cave, whilst at Lunel they have been preserved in consequence of the greater size and dryness of the chamber in which they were deposited."

Coprolites

Buckland returned to his musings on faecal products in 1829. A friend of the famous "fossilist", Mary Anning (1799-1847), Buckland often collected with her from the Lias cliffs and foreshore of the Lyme Regis and adjacent successions. The dark grey structures, up to 10 cm long, resembling "elongate pebbles, or kidney-potatoes" and occurring in the Lias, were called "Bezoar stones" by the locals, referring to their supposed superficial similarity to the concretions developed in the stomach of the oriental Bezoar Goat (*Capra aegagrus*), used extensively in medicine as a universal antidote to poisons, particularly during the 16th and 17th centuries. He later wrote that "these Coprolites are so abundant that they lie in some parts

***Figure 10.** Hyaena coprolites, Album Graecum, from Kirkdale, on display in Oxford University Museum (OUM).*

of the lias like potatoes scattered in the ground" (Buckland, 1836 p188). Buckland concluded that these were fossilized faeces from the ichthyosaurs, based upon their co-occurrence with those marine reptiles, and their contents - undigested bones and scales of fishes such as *Dapedium politum*, as well as the bones of small ichthyosaurs (Fig. 11). He noted the spiral form of some of the specimens, their presence in the pelvic region of the body cavity in certain ichthyosaur specimens, and the chemical analyses showing a composition similar to that of the *Album Graecum* he had described from Kirkdale (Buckland, 1829a). A later comment in the same volume described "the bony rings of the suckers of cuttle-fish … frequently mixt with the scales of various fish, and the bones of fish, and of small Ichthyosauri in the bezoar-shaped faeces from the Lias at Lyme Regis" (Buckland, 1829b p142) (Fig. 12). This time, William Prout, the physician and chemist, was let loose on performing the chemical analyses; he concluded that the black colouring was of the same chemical composition as material in fossil teuthoid ink sacs, and that they were therefore amongst the prey on which ichthyosaurs fed (Buckland, 1829b).

Similar specimens were noted from the Late Triassic Rhaetic Bone Bed (then called the "Lias bone bed") and the basal Carboniferous Limestone of the Bristol District. Beginning to develop a taxonomic nomenclature (probably the first in ichnology), Buckland proposed that these black fossil faeces should be called "Nigrum graecum" on the basis of their colour (Buckland, 1829b p142; a name he later [1835] credited to a Mr Dillwyn), and that specimens of demonstrably piscine origin (found within the body cavity) should be called Ichthyo-coprus; ichthyosaur faeces would be Sauro-coprus, and the term *Album Graecum* should be replaced with Hyaino-coprus. Referring obliquely to the earlier descriptions by Woodward, Parkinson and Mantell, he noted that the spiral faecal structures were very similar to the "Iuli" or fossil fir cones of the chalk, and that these Cretaceous specimens were therefore also faecal in origin, and should be referred to as *Copros iuloides*. His final proposition was that he would "include them all under the generic name of Coprolite" (Greek, copros = dung, lithos = stone).

Figure 12. *Coprolite 76 mm long from Lyme Regis, described by Buckland as containing "bony rings of the suckers of cuttle-fish" but which are actually fish teeth (photo: OUM).*

This lecture formed the basis of a fuller treatment of the subject (Buckland, 1835). Here, Buckland freely admitted that he and W.D. Conybeare had been confused over the identities of the objects now identified as fossil faeces earlier in their careers, originally believing them to be particularly dense masses of heavily rolled bone or palatal teeth. This, together with Buckland's new conclusions, must have struck a chord with the broader scientific community; colleagues rooted out a plethora of items that fitted Buckland's descriptions very closely. Mr J.S. Miller furnished specimens from the Rhaetic Bone Bed and Carboniferous Limestone of the Bristol district. Mr Jelly (probably Rev. Henry Jelly of Bath) provided specimens from the Kimmeridge Clay of the Oxford district, and Reverend Benjamin Richardson of Farleigh Hungerford near Bath provided specimens from the Wiltshire Greensand. Gideon Mantell and the Philpott sisters of Lyme Regis also made material available to Buckland.

John Josias Conybeare was, like his brother, W.D. Conybeare, a keen geologist. He conducted fieldwork with Buckland in Devon and Cornwall during the summer of 1813. In 1808, as Vicar of Bath Easton he had retrieved specimens of the Rhaetic Bone Bed ("lias breccia") from a trial borehole sunk in an attempt to find coal; the coprolites were turned over to Buckland.

Robert Anstice of Bridgewater, rather appropriately to this topic, was appointed Commissioner of Sewers and charged with overseeing various projects to drain the Somerset Levels (Dance, 2003). Anstice started collecting for his own personal museum just before the close of the 18th century and was a regular correspondent of Buckland's in the 1820s. He wrote to Buckland on 13 April 1829, enclosing some specimens of Rhaetic Bone Bed from Blue Anchor Point on the north Somerset Coast, as well as water colour sketches of two specimens, both containing numerous coprolites, in one case associated with a fin spine of *Nemacanthus monilifer*, and in the other with a jaw fragment of *Severnichthys acuminata* (Figs. 13). He apologised for being unable to prepare the coprolites out of the bed, writing "You are well aware of the difficulty of extricating from their matrix any of the subjects contained in this very impracticable stone", but lauding Buckland's efforts with the comment that "No fossil subject ever presented a greater difficulty of explanation to me than these Pupae shaped bodies have", but that "I have no doubt but that you have cleared up the mystery" (OUM Coprolite File). It was another 150 years before coprolites from the Rhaetic Bone Bed received further serious attention (Duffin, 1979; Swift & Duffin, 1999).

As the list of formations from which coprolites were identified grew, Buckland tinkered a little with his nomenclatural scheme, referring now to "Iulo-eido-coprolites" from the Chalk, and "Amiacoprus" a

Figure 13. *Water colour sketches by Robert Anstice of (above)* Nemacanthus monilifer *fin spine and coprolites and (below) jaw fragment of* Severnichthys acuminatus *and accompanying coprolites, both from the Rhaetic Bone Bed of Blue Anchor Point, north Somerset (photos: OUM, Buckland papers, Coprolite File).*

specific type of ichthyocoprus located within the body cavity of a Cretaceous specimen (Fig. 14) described as *Amia lewesiensis* by Mantell (1833). He reserved the name Ornithocoprus for the recently described guano deposits of Peru (Buckland, 1835).

Some of the specimens described by Buckland are illustrated in the accompanying paper by Ford and O'Connor (this *Mercian Geologist*). Buckland found that coprolites from Lyme Regis showed considerable diversity. Their colour varied from ash-grey through to black; they ranged in size up to around 10 cm; some were amorphous, while others showed spiral marking,

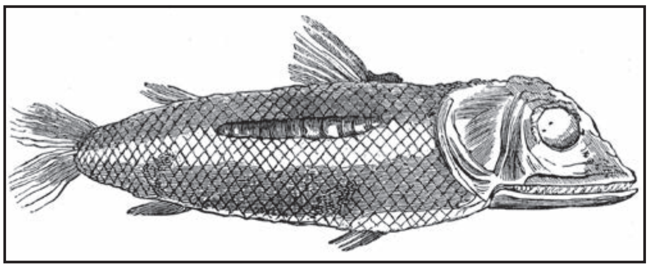

Figure 14. *The Cretaceous* Amia lewesiensis *that contained "Amiacoprus" a specific type of ichthyocoprus within its body cavity (from Mantell, 1833).*

Figure 15. *Spiral coprolite 122 mm long, from Lyme Regis, figured by Buckland (1835) (photo: OUM).*

the number and distribution of which also showed some diversity (three to six full convolutions); their contents varied considerably with fish scales and ichthyosaur bones; supposed suckers of cephalopods are actually the tooth-bearing bones of small bony fishes such as *Eomesodon* (Fig. 12).

Buckland found spiral coprolites (Fig. 15) particularly interesting. He had some specimens cut and polished to show their internal structure (Fig. 16), and he dissected several extant rays and scyliorhinid sharks (dogfishes) in order to study the spiral valves of their intestinal tracts. Anxious to see if such a structure would confer spiral structure on faecal material passing through it, he set out to test the hypothesis with a typically innovative technique. He injected the intestines with Roman cement. Despite its name, this was a highly successful, quick setting (5 to 15 minutes) hydraulic cement developed by James Parker in the 1780s but patented only in 1796, and made by burning and then grinding down clay-rich septarian nodules. He found that he could produce "artificial coprolites that in form are exactly similar to many of our fossil specimens" (Buckland, 1835 p234). A similar experiment was performed over a century and a quarter later by Zangerl and Richardson (1963). Buckland visualised the process of spiral coprolite formation as follows (Buckland, 1836 p194) : *The form is nearly that which would be assumed by a piece of riband, forced continually forward into a cylindrical tube, through a long aperture in its side. In this case, the riband moving onwards, would form a succession of involuted cones, coiling one round the other, and after*

Figure 16. *Sectioned and polished spiral coprolite 60 mm long, from Lyme Regis, figured by Buckland (1835) (photo: OUM).*

a certain number of turns within the cylinder, (the apex moving continually downwards,) these cones would emerge from the end of the tube in a form resembling that of the Coprolites . . . In the same manner, a lamina of coprolitic matter would be coiled up spirally into a series of successive cones, in the act of passing from a small spiral vessel into the adjacent large intestine. Coprolites thus formed fell into soft mud, whilst it was accumulating at the bottom of the sea, and together with this mud, (which has subsequently been indurated into shale and stone,) they have undergone so complete a process of petrifaction, that in hardness, and beauty of the polish of which they are susceptible they rival the qualities of ornamental marble. Closer inspection of the spiral coprolites from Lyme Regis revealed "a series of vascular impressions and corrugations on the surface of the coprolite, which it could only have received during its passage through the windings of this flat tube [the spiral valve]" (Buckland, 1836 p153).

In his later volume for the *Bridgewater Treatise* series (Buckland, 1836 p188), Buckland was able to incorporate even more examples of Formations yielding coprolites, from information and material sent to him from home and abroad in response to his earlier papers. Georg Friedrich Jaeger wrote to him from the Eberhard-Ludwigs-Gymnasium in Stuttgart where he was Professor of Natural History and Chemistry (Warth 1992), sending specimens, drawings and descriptions of spiral coprolites from the Alaunschiefer (Lettenkeuper, Ladinian, Middle Triassic) of Gaildorf in Baden Württemberg, Germany, probably the famous Alum mine (Buckland, 1836 p149; letter 2 April 1833, OUM Coprolite File). Similarly, James Ellsworth DeKay, later of the Geological Survey of New York State, sent him a coprolite cast from New Jersey (Folk, 1965).

Other members of the British geological fraternity also responded. Samuel Hibbert, the Mancunian who trained as a physician in Edinburgh, but foreswore medicine for antiquarianism and geology, is probably best known for describing and mapping the rocks of Shetland (Ware, 1882). He noted that coprolites were abundant in the lacustrine Burdiehouse Limestone of the Dinantian Oil Shale Group near Edinburgh. Buckland's former student, Sir Philip de Malpas Grey Egerton, then Member of Parliament for Chester, located similar specimens in the Coal Measures of Newcastle-under-Lyme, Staffordshire. Sir Walter Calverley Trevelyan, a diligent collector of all manner of natural history specimens, recognized coprolites in the Coal Measures around the fishing village of Newhaven near Leith, on the Firth of Forth in Scotland. Buckland visited the section in September 1834 with Trevelyan and Lord Greenock (Charles Murray Cathcart, 2nd Earl Cathcart), discoverer of the rare mineral form of CdS, which was subsequently named after him (greenockite). The party found a series of clay ironstone nodules with coprolite nuclei "strewed so thickly upon the shore, that a few minutes sufficed to collect more specimens than I could carry" (Buckland, 1836 p199). Buckland also notes that, *"These nodules take a beautiful polish and have been applied by the lapidaries of Edinburgh to make tables, letter presses, and ladies' ornaments, under the name of Beetle stones, from their supposed insect origin."* It may be these nodules that were cut, polished and fashioned into the famous coprolite table, now housed in the Philpott Museum in Lyme Regis.

Buckland was renowned for his rather earthy sense of humour. Indeed, Charles Darwin wrote of him in his *Autobiography*, "though very good-humoured and good-natured, [Buckland] seemed to me a vulgar and almost coarse man. He was incited more by a craving for notoriety, which sometimes made him act like a buffoon, than by a love of science". He was certainly not averse to a joke at his own expense and reveled in the cartoons and doggerel which flowed from the fertile minds and pens of some of his friends. Coprolites were, of course, grist to the mill for this type of ribaldry.

Philip Bury Duncan, a stalwart of the Bath Royal Literary and Scientific Institution (Chairman 1834-1859), for example, wrote to Buckland with some oft-quoted verses :

Approach, approach ingenuous Youth
And learn this fundamental truth
The noble science of Geology
Is bottomed firmly on Coprology
For ever be Hyaena's blest
Who left us the convincing test
I claim a rich Coronam Auri
For these Thesauri of the Sauri

The couplet at the end links the golden crown with the 'treasures' (thesauri) of the extinct saurians, these treasures being their faeces. Duncan also delivers some lines of Latin :

Avia Pieridum peragro loca nullius ante
Trita solo, coecas iuvat explorare ferarum
Speluncas, iuvat et merdas exquirere priscas
Saurorum duro et vestigia quaerere saxo

These lines are modeled on Lucretius' *De Rerum Natura 1*, lines 925-927. An English translation of the classical original reads as follows :

I wander through the pathless places of the Muses,
Previously trodden by the foot of none.
I am glad to approach the virgin springs,
And drink; glad, too, to pluck new flowers

Duncan's modified version can be translated as :

I wander through the pathless places of the Muses,
Previously trodden by the foot of none.
I am glad to explore the hidden caves of wild beasts,
glad, too, to search out ancient turds of lizards,
And to look for traces in the hard rock.

On a fold of the envelope he wrote : *"Tear off the other side for Mrs B for she must know nothing of the Bona Dea Coprologia - Cloacina Ocaeaningae"*. Even here, he is playing a coprolitic theme. The Good Goddess Coprologia is linked with the Cloacina Oceaningae or oceanic sewer, in the oblique reference to

Rome's sewage system, the Cloaca Maxima, which ran into the River Tiber and thence to the sea. In a parallel with the Roman sewage system, Duncan refers to the oceanic sewer – the Lower Jurassic sea that became the repository for the coprolites produced by the living community of reptiles and fishes within it.

This theme was taken up pictorially by Thomas Henry de la Beche, the founder of the Geological Survey who lived much of his early life in Lyme Regis, in the execution of his famous watercolour (1830) "*Duria antiquior – a more ancient Dorsetshire*" – the first attempt at reconstructing an ancient ecosystem (Fig. 17). This 'cartoon' was copied by George Scharf, artist to the Geological Society as a lithograph that was then sold, mostly to Fellows of the Society, for two pounds and ten shillings each, to assist the Anning family, who were then suffering hardship. De la Beche's depiction of the Lower Lias sea scene shows a virtual rain of coprolites to the sea bed as many of the subjects, particularly the marine reptiles in his sketch go about their daily business of eating and being eaten. The sea floor is similarly littered with coprolitic debris.

Later work

The response to Buckland's work was immediate and enthusiastic. His close friend, Louis Agassiz, who was in the midst of a massive, fundamentally important five-volume work on fossil fishes (Duffin, 2007), was called upon to identify isolated scales enclosed in Carboniferous and Lower Jurassic coprolites; the fact that he could do so immediately was a source of some wonder to Buckland (1836). At the same time, Agassiz shared some conclusions over ribbon-like fossils from the Solnhofen Plattenkalk (Tithonian, Late Jurassic) described as annelid worms by Goldfuss, and accordingly named *Lumbricaria*. Agassiz believed these structures to be fossilised fish intestines, referring to them as Cololites (Buckland, 1836). In defence of his suggestion, Agassiz made close observations of the decomposition sequence shown by dead fish in the lakes of his native Switzerland, anticipating similar work by Wilhelm Schafer (1972) by over a hundred years. Carcasses, re-floated belly upward by the accumulation of gaseous products of putrefaction, eventually burst open through the abdomen. The intestines are able to exit the body through the rent, become detached from the remainder of the carcass, and float away in a coherent mass, eventually being stranded on the shore. This interpretation of *Lumbricaria* is still accepted today (Frickhinger, 1994). Georg Graf zu Münster (1830) was quick to identify coprolites from the same locality and other stratigraphical levels in Germany. Robert (1832-3) was the first to record coprolites from France (Oligocene), but was followed by Robertson (1834) who may have been the first to describe a dinosaur coprolite from the French Cretaceous (Lambrecht, 1933). A number of papers followed, mostly reiterating previous work or citing new records of coprolites from different localities, and filling gaps in their stratigraphical distribution (including Girard, 1843).

In 1844, Georges Louis Duvernoy, professor of Natural History at the Collége de France in Paris and former co-worker of Cuvier, suggested that some fossils with a spiral form might be "urolites" ("fécès urinaires") rather than coprolites ("fécès alimentaires"). This stemmed from his work on the Chameleon, whose faeces possess a simple cylindrical morphology, but whose solid urine has a spiral structure. The producers of such fossil urolites would be limited to lizards and snakes (lacertilians and ophidians).

The earliest reference on invertebrate coprolites is that of Christian Erich Hermann von Meyer (1852),

Figure 17.
"Duria antiquior – a more ancient Dorsetshire", the water colour sketch by Thomas Henry de la Beche (photo: National Museum of Wales).

the doyen of German palaeontology and founder of the journal *Palaeontographica*, who discussed the possibility of faeces from insect larvae in lignitic deposits at Salzhausen.

With the idea of fossil faeces (coprolites), fossil intestines (cololites) and fossil urine (urolites) established in a gradually expanding literature, there was little controversy as publications described new finds, often with chemical analyses. However, Fritsch (1895) and Neumayer (1904) concluded that coprolites with a spiral form were actually fossilised valvular intestines. As such, it could be argued that they fell within Agassiz's definition of cololites, but Fritsch proposed the name 'enterospirae' for them (Duffin, 1979). Neumayer (1904) distinguished two morphologies of spiral coprolite: heteropolar coprolites are spindle-like with relatively closely spaced turns concentrated at the more obtuse or 'anterior' end of the specimens; amphipolar forms possess more widely spaced spiral turns more evenly spaced along most of the length of the relatively blunt-ended coprolites. The debate over the coprolitic versus cololitic origin of spiral forms resurged with descriptions of heteropolar coprolites from the Permian of Kansas by Williams (1972). Thin sections of these revealed bifurcating mucosal folds arising from the whorl interfaces, showing a strong similarity to spiral valve structure and leading Williams to conclude that they are true enterospirae. Further specimens with similar histology from the Niobrara Formation (Late Cretaceous, USA) added weight to this hypothesis (Stewart, 1978). However, McAllister (1985) showed that the spiral valve of extant *Scyliorhinus canicula* is able to extrude faecal material into the colon, and then expel it from the body while retaining its undistorted spiral riband form; sections of hardened examples of these modern coprolites showed similar mucosal fold histology to that described for the Permian forms. At the current state of knowledge, it is likely that spiral faecal structures could be fossilised spiral valvular intestines (enterospirae), fossil colon contents (cololites *sensu lato*) and true coprolites.

A recent review by Hunt *et al*. (2007) made the comment that "coprolites are the least studied and most under-sampled vertebrate trace fossils". Building on earlier work (Hunt et al., 1998), the need to produce a taxonomic framework led to the definition of a number of coprolite ichnotaxa, partly embracing Buckland's original specimens described some 170 years earlier. Saurocoprus, a name introduced by Buckland (1835) is formally defined as one of six coprolite ichnotaxa, and *Saurocoprus bucklandi* is applied to heteropolar coprolites from the Lyme Regis Lower Jurassic – a fitting tribute to the father of coprolite research, whose fundamental work and innovative insight laid the foundation for a rich topic of geological enquiry. By 1968, at least 376 publications on coprolites were known (Hantzschel et al, 1968), and research has continued unabated since on an ichnological group that is known from Ordovician times onward; some surprising results include the description of possible coprophagous arthropods (Duffin, 1978), dermestid beetle debris stripping embryos inside dinosaur eggs (Cohen et al., 1995), and even a new Oligocene snake named, aptly, *Coprophis* (Parris & Holman, 1978).

Mundane they might be, and a source of humour and fascination they certainly are, but who would have thought that in the excited conclusion to a careful piece of analysis by William Buckland they could also take on an air of romanticism: *"In all these various formations our Coprolites form records of warfare, waged by successive generations of inhabitants of our planet on one another: the imperishable phosphate of lime, derived from their digested skeletons, has become embalmed in the substance and foundations of the everlasting hills; and the general law of Nature which bids all to eat and be eaten in their turn, is shown to have been co-extensive with animal existence upon our globe; the Carnivora in each period of the world's history fulfilling their destined office,—to check excess in the progress of life, and maintain the balance of creation."* (Buckland, 1835 p235)

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The Physical Geology of Beavers

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Abstract: Wild beavers (*Castor* sp.) are set to return to Britain. Beavers appear to have been present during the Chelford Interstadial at Chelford c100 ka BP, and the physical nature of the beaver-created environment, including dams, lodges and lakes, is compared with modern Canadian sites. The chronology of beaver presence in Britain includes both extinction and reintroduction. Both the importance and implications of beaver activity on the character of the geological record associated with the fluvial sedimentology of floodplain environments is reviewed. A case study is provided from the Kennet valley floodplain in southern England. A greater awareness of beaver geology is advocated for an improved understanding of prehistoric floodplain stratigraphy, and for possible future riparian environmental management.

The year 2009 is a landmark in the history of arguably the most charismatic of Britain's lost species – the beaver. Eleven animals, in four families, were transferred in May from southern Norway to Knapdale Forest, in south west Scotland (NGR NR 800900), an area with several freshwater lochs. Their release into the wild will be the culmination of a protracted campaign by ecologists for beaver reintroduction into the British fauna, and has been won against ill-informed opposition from landowners and fishing organisations. If this pilot scheme is successful, it will undoubtedly lead to similar reintroductions in parts of England and Wales.

This paper has had a very long gestation period, as the writer's first encounter with beaver geology came in the mid 1970s in Cheshire, England, when tentative taphonomic evidence indicative of beaver presence was discovered in periglacial alluvial sands (Chelford Sands Formation) beneath glacigenic sediments (Stockport Formation) correlated with the Last Glacial Maximum (Worsley, 1967). At that time, silica sand quarrying at the Oakwood Quarry near Chelford was exposing the Chelford Interstadial sequence in its type area, and sections showed for the first time that the organic-rich interstadial sediments formed the infill of an incised palaeochannel system draining towards the northwest. Burial compaction of the infill by later sediments, and probably also through loading from glacial ice, had reduced an original thickness of several metres to some 0.5 m of felted peat and organic mud. A recent summary of the Chelford area Quaternary geology is given in Worsley (2005).

Abundant detrital sub-fossil tree fragments and stumps formed part of the palaeo-channel infill and these retained their original dimensions (<1.9 m in diameter) in contrast to the smaller branch fragments which showed significant flattening. Only rarely were tree stumps seen *in situ*. During quarrying, the operator separated the large material from the sand and peat and placed these in dumps. Recurrent examination of these dumps over a decade revealed that some of the tree stump tops were conical in shape, rather than being fractured, as is usually the case with snapped tree falls. These conical terminations appeared reminiscent of those reported in the literature as being the product of beaver tree felling. To test this possibility, a large cone-like tree stump (Fig. 1) was placed in the path of two separate field groups of over 100 participants when they visited the quarry during the Birmingham INQUA congress in August 1977. Without prompting

***Figure 1**. A sub-fossil tree stump extracted from a flood facies within the type Chelford Interstadial sequence in the West Oakwood Quarry in east Cheshire. It has a conical top similar to those produced by beaver felling, but had later been subject to rolling during fluvial transport. It was exhibited to the visiting INQUA Congress field party in August 1977.*

and without exception, all the North American visitors opined that this stump was a product of beaver felling activity. In addition to the conical stumps, parts of the sand facies within the channel contained high concentrations of chaotically dispersed fragmented woody material along with the fruits of pine and spruce, suggesting an origin as flood debris. The question arises as to whether the flooding was climatically induced or was related to the bursting of a beaver dam.

Shortly after this meeting, the writer commenced an academic year in Ottawa, Canada, which afforded the opportunity for field studies of beavers in Ontario and Québec under both summer and winter conditions. The outcome of this experience was increased confidence in the hypothesis of beaver presence during the Chelford Interstadial. At a 1978 meeting of the Quaternary Research Association in Cambridge, which had a Quaternary vertebrate theme, a paper and allied demonstration of contemporary beaver-cut wood material together with some comparative Chelford material was presented (Worsley, 1978). Later field observations of beaver have been made in various parts of the Americas from the Mackenzie Delta in Canada to Argentinean Tierra del Fuego.

Beaver species

Beavers are classified as rodents and are assigned to the genus Castor. This genus normally consists of an Old and a New World species, namely the Eurasian beaver *Castor fiber* Linnaeus 1758 and the very closely related Canadian beaver *Castor canadensis* Kuhl 1820. . A globally extinct Giant Beaver, named *Trogontherium cuvieri* Fischer 1809 in Europe did not survive after the Middle Pleistocene (Hoxnian interglacial) in Britain (Mayhew, 1978) although a similar species, *Castoroides*, survived in North America until the commencement of the present interglacial c10 ka BP.

***Figure 2**. A short beaver dam built with neatly arranged branches on its downstream face, across a small creek in the Eardley Plateau, Gatineux National Park, Québec, Canada.*

The beaver environment

In his book *Mammals of Canada*, Benfield (1974, p158) wrote ‘Almost every Canadian is familiar with the work of the beaver. It is one of the few animals, aside from man, that can profoundly change its own habitat, and for this reason it has earned the title ‘engineer of the world’’. Over two centuries earlier in Sweden, Carl Linnaeus wrote of the beaver - ‘in the art of building he is surpassed by no living creature except man. With his admirable cleverness he regulates the level of the water outside his house, he digs channels and builds roads for the transport of his necessities from the forest’. Prior to twentieth century reintroduction, the beaver became extinct in Sweden c1870. Alas, few Britons are similarly informed, simply because their native beaver has been extinct for several centuries, and consequently an appreciation of the environmental impact of beavers is not normally part of their experience. Beavers are

***Figure 3**. The dam shown in Figure 2 impounded a lake within a forest, where the beavers had constructed a lodge that can be seen rising above the lake surface. To the right of the lodge, the top of a submerged pile of cut tree branches is the winter food cache.*

Figure 4*. The beaver lodge in Figure 3, seen some 10 months later, in August 1978. The lake is now drained, and the full lodge structure can be seen with its foundations on the former lake bed. It is likely that the lake drained during the previous winter as a result of human interference with the dam.*

exceedingly industrious and apart from wood cutting to supply material for dam and lodge building and food stores, are also engaged in digging and transporting sediment, hauling clasts, and excavating canals.

There are numerous excellent accounts of beaver biology (Wdowińscy & Wdowińscy, 1975; Novak, 1976; Pinder, 1980 a & b; Coles, 2006; Cole *et al,* 2008). Accordingly, the emphasis here will be on physical environmental aspects of beaver ecology as these are directly related to the geological record; there are five main factors relevant to beaver physical geology.

Dams and allied lakes or ponds

Undoubtedly the most dramatic activity of beavers is their instinctive ability to construct dams across streams to create artificial lakes. In plan, dams are normally convex in the downstream direction. Typical lengths are in the 10-100 m range and heights from 2-3 m are common (Fig. 2); but there are exceptions, and lengths of over 200 m are known. Any kind of available material is used in dam construction, although the core is normally a network of tree branches. On the dam's upstream side, sediment ranging from stone clasts to mud is used to create an impermeable seal. In the lakes upstream of the dams, the beavers concentrate their daily activity and in particular use the water to float-transport wood material that they have cut. In regions where lakes normally freeze in winter, lake water depth is crucial, although even in severe winter climates annual lake ice rarely exceeds 1 m in thickness. Beavers have an uncanny ability to control the minimum water depth necessary for winter survival. The degree of dam building is dependent upon local circumstances; the more southerly populations in France tend not to be so dependent on dams, as they inhabit rivers with larger discharges and burrow into the banks.

Field observations on the Canadian Shield indicate two basic types of beaver lake, each depending upon the nature of the local bedrock relief. In high relief situations, such as a linear steep-sided valley, the main dam is usually a relatively short, high structure, and is augmented by one or more additional dams downstream, seemingly built as security features should there be a problem with integrity of the main structure. The lake upstream of the dam is usually linear in shape and contains a single lodge. In contrast, low relief areas necessitate much longer dams that tend to be lower in overall height. However, the upstream lake inundates a much greater area and may contain several lodges that accommodate more than one family. Significant areas of swamp commonly characterise the more distant lake shores from the dam. In the Gatineux National Park, Québec, lodges within the peripheral marshes have access afforded by beaver-dug canals over 120 m long. The lakes also enable extended foraging around the perimeter, but for safety considerations this is normally restricted to a zone about 60 m inland from the lake shore, except where canals have been dug enabling an extension of this zone to at least 100 m from the main shore. On average a single family has a territory extending for some 3 km along the valley axis. Creation of a new lake results in the flooding of the formerly forested, freely draining area. Any pre-existing vegetation cover will soon be killed and dead trees will protrude above the lake level for several years until they are felled by storm events.

Lodges and burrows

The lodge is built within the beaver lake and consists of a mixture of old sticks and mud. Average dimensions of lodges are <10 m in diameter and <3.7 m in height, although it has to be remembered that the lower part of island lodges are submerged (Figs. 3 & 4). Lodges

Figure 5*. An in situ birch stump recently felled by a beaver in Gatineux National Park, Québec.*

Figure 6. A half-felled cottonwood tree in the Dinosaur Provincial Park, Alberta, with a pile of shavings produced by the beaver gnawing. Scale provided by Tom Worsley (aged 4); he was not impressed since when he went to bed the tree was intact, and the beaver gnawing had taken place overnight while he slept in a tent beneath the same tree.

are entered via underwater tunnels excavated through the debris pile, and have an interior chamber with a platform just above lake level. The outer surfaces are invariably plastered with mud and short sticks. The apex is left clear as it acts as an air vent to the living chamber below. A lodge serves as both an insulated home in winter, and also as a refuge from predators. Typically, Canadian beavers construct their lodges either within the flooded zone (island lodge) or on the bank of a lake or stream where the sediment is soft. The latter can be fortified by a land-based structure of aquatic lodge form. Adjacent to the lodge, the beaver builds a submerged winter food cache in the form of a pile of cut branches, which may be nearly as large as the lodge itself. There has been some inconsistency in the older literature as to the behaviour of European beavers, even to the extent of suggesting that they do not build dams or construct lodges at all. It appears that neither is true, although some European beavers have a greater tendency to adopt natural bank cavities or create artificial burrows as lodges.

Gnawed and felled wood and stripped bark

Beavers fell trees in order to acquire branches for building their dams, food stores and lodges. Trees with diameters of over 1 m are within their capabilities, and once felled the branches are dismembered. A felled tree is left with a conical stump top 0.1–0.4 m high (Fig. 5) and the corresponding main trunk displays a similar conical end. Partially felled trees are common, suggesting that the beaver was disturbed while gnawing (Fig. 6). The area around the stump is littered with the curled shavings resulting from the beaver's wood cutting. As a source of winter food, beavers often strip the bark from branches too large to remove from the site of growth to their lake (though they feed on aquatic and herbaceous plants in summer). They also cut low scrub such as willow and birch, and similarly remove the bark for nourishment. Wood chewed or gnawed by beavers bears characteristic markings, which are known in the geological record as far back as the Cromerian.

Lake drainage and site abandonment

After a number of years the food resources around a beaver lake become depleted, and ultimately a beaver family will move to a new area. The existing dam will then be no longer be under beaver maintenance, and progressively seepage will lead ultimately to lake drainage. Alternatively, a catastrophic event might terminally damage the dam with rapid emptying of the lake. Within what would have been woodland prior to lake creation, the old lake bed will convert to a clearing within the woodland or forest. If the beaver does not return to the site, swampy organic-rich meadows can develop where grazing can retard tree recolonisation.

Outburst flooding consequent to dam failure

Extreme weather events can cause excessive inflows into beaver lakes so that the dams can be overwhelmed. Rapid drawdown of the lake water can lead to catastrophic flooding downstream. Butler (1989) reported that clasts up 1 m in diameter can be transported and that one particular flood event caused four casualties and deposited a survivor 4 m up in a tree! At various times, both Canadas' transcontinental railway lines have been severed by flooding consequent on beaver dam failure.

Dating of Colonisation and extinction

The earliest known natural colonisation by *Castor fiber* in Britain is from the Cromerian Interglacial (c0.5 Ma). A mass of beaver gnawed branches (Fig. 7) was found in a coastal exposure of the Cromer Forest Bed near Bacton, and was thought to be part of a dam (McWilliams, 1967). However, *C. fiber* may have been present as early as the late Pliocene. After the Cromerian,

Figure 7. Beaver-gnawed small-diameter branches that could easily be taken for contemporary material; these were obtained from the Cromerian interglacial sediments of the north east Norfolk coast and hence are some 500,000 years old (now in Castle Museum, Norwich).

beaver appears to have been present in Britain during each of the subsequent warm (interglacial) stages (Stuart, 1982). One of the classic Palaeolithic sites of late Middle Pleistocene age (MOI Stage 9) at Stoke Newington, London, may have yielded beaver-cut birch branches. Lack of sites makes it difficult to assess whether beaver was able to persist during the intervening cold stages. Similarly, it is unknown whether it survived the Devensian LGM c20 ka BP, when permafrost was widespread in southern England. The crucial factor here would have been summer temperature, as the average July 10ºC isotherm determines the position of the treeline, and beavers thrive on continuous permafrost in the Mackenzie Delta, northwest Canada (Gill, 1972). If beaver was banished during the LGM, then it must have re-colonised Britain from southern or eastern refugia before the marine transgression (following the LGM low stand of -120 m OD) drowned the land bridge that crossed the site of the present English Channel. The critical threshold height in this instance would have been some -37 m OD, and initial submergence of this corresponds to global sea level at c 9.5 ka BP. Beavers appear never to have colonised Ireland.

The first chronologically well constrained indications of beavers after the LGM occur at the two most important Mesolithic (early post-glacial) settlement sites of Thatcham in the Kennet Valley and Star Carr in the Vale of Pickering. These sites date from the onset of Holocene interglacial warmth at respectively c10 and c9.5 ka BP, and both include beaver in their extensive faunal lists. Coles (2006) lists 26 radiocarbon assays on beaver bones and these bracket the 9.3–1.2 ka BP time span. Within the last thousand years, human overkill, and possibly also loss of habitat, are likely to have been the main causes of extinction. Beavers were hunted for their skins, meat and their glandular secretion (castoreum) for medicinal purposes (it has similarities to aspirin). The demand for beaver meat was enhanced in the medieval period since the Catholic church anomalously classified beaver meat as fish and hence it could be eaten on Fridays! The precise date of the extinction is debateable, but an early medieval date for England and Wales is probable. However a recent assessment of the historical documentary evidence has concluded that survival as late as the 18th century on the River Wharfe in Yorkshire is possible (Coles, 2006). Even on the European mainland beaver came perilously close to extinction due to hunting at the start of the 20th century, and similarly in North America the beaver was almost wiped out by 1930. Fortunately, following near extinction, more enlightened attitudes to conservation have resulted in dramatic recoveries on both continents.

Pioneer reintroductions in Britain

European beaver is the captive species now normally found in British zoos. In 1729, William Burnet, then Governor of New England in Boston, presented a young live beaver to a Mrs Clayton, a bedchamber servant to Queen Caroline. Later she was promoted to be Mistress of the Robes and was appointed Viscountess Sunden. Burnet wrote, '…which I have not heard has yet been seen in England. As this is a famous animal for its industry and policy, and, I think, peculiar to America … it will require to be kept within stone walls, or iron bars, or be chained, because it will eat through anything of wood …'. (Thomson, 1847).

At three British country estate locations in the late 19th century, Canadian beaver colonies were established. The first was in Sotterley Park, Beccles, Suffolk in 1870 but this was soon abandoned as the beavers escaped confinement and their tree felling activity was judged unacceptable. The second attempt was from 1874 in a pine wood enclosure near Rothesay on the Isle of Bute, but by 1890 they had died out (Black, 1880; Harting, 1880; Hawks, 1883). It is possible that the Bute colony consisted of at least some European beaver (Gibson, 1980). A third colony was created in 1890 at Leonardslee Gardens, southeast of Horsham, in Sussex (Loder, 1898). Here beavers were introduced into an enclosure on the floor of an incised valley where a dam was built and a burrow lodge was created on the shore. In 1896 the enclosure was extended downstream and a further but larger dam ensued, partially submerging the former. These beavers had either died out or were moved to zoos by 1948. Waterfall Lake, which is the successor to the beaver lake, has an island with the dimensions of a degraded beaver lodge in shallow water close to its shore. A successful attempt to breed *Castor fiber* was at the Norfolk Wildlife Park in 1973. Escaped beaver are known in recent decades in Essex, Somerset, Surrey and northern Scotland.

***Figure 8**. Trails in sandy sediment produced by beavers walking from a creek to the attempted felling site shown in Figure 6, in Dinosaur Provincial Park, Alberta.*

Under Article 22 of the European Union Habitats Directives (EC/92/43), member states are obliged to consider reintroducing species to their territory which were once present, and also those which are endangered. As Kitchener & Conroy (1996, p156) have observed 'unfortunately many of our extinct mammals are big and most have sharp teeth and claws, as well as a bad public-relations image'. Despite this, the directive has given an impetus to reintroducing the European beaver into Britain, aided by the fact that it is quite small and vegetarian (big teeth not withstanding). Scottish Natural Heritage is taking a lead role.

Geological consequences of the beaver

Probably the first suggestion that beaver activity might have important repercussions for Quaternary geological sedimentary process was advanced by Ruedemann and Schoonmaker (1938). Rudolf Ruedemann was engaged in geological mapping in the area east of the New York state capital of Albany. In hilly terrain he encountered a series of gently sloping alluvial plains forming valley floors that typically were 7-15 km long by 0.5-3.0 km wide. These plains had been previously interpreted as former lacustrine features, but the gradient and underfit of the drainage systems indicated that another process was influencing their fluvial geomorphology. Accordingly Ruedemann proposed that a dynamic complex of beaver dams constructed over post-glacial time had induced widespread aggradation on the valley floors. An original longitudinal profile through a succession of infilled ponds would have given a stepped profile, but with time the individual beaver pond infills would have merged to produce a more regional planar feature. He asserted that the importance of this animal-induced sedimentation had hitherto been overlooked, and illustrated this by noting that in Fenneman (1938), a just-published regional geomorphology textbook, beaver geological activity was not mentioned. Alas the same can be said for one of the more erudite recent American textbooks of geomorphology, Bloom (1991). Yet Ruedemann and Schoonmaker were able to observe that the United States Government policy to encourage beaver reintroductions in the northwestern states in order to naturally control river bank erosion ('beavers as loyal government officials') had reduced erosion at a cost of a sixtieth of a human-created structure.

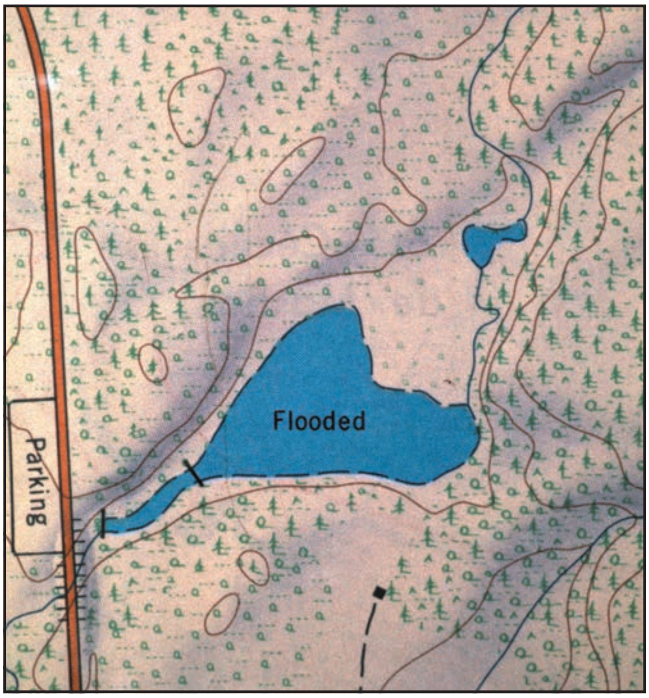

Figure 9. A beaver-dammed lake near Old Chelsea, Gatineux National Park, Québec. Of the two dams, one parallels the main road, while an upstream dam is seen in Figure 10.

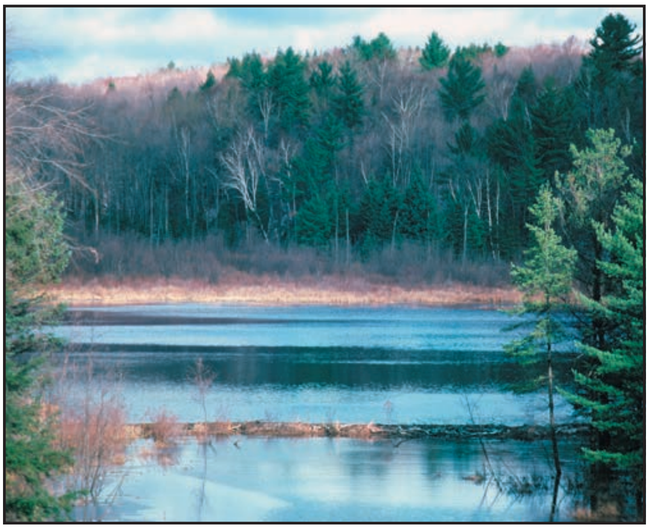

Figure 10. The beaver-created lake at Old Chelsea with the upstream of its two dams in the foreground.

A development of the above idea came with a study of beaver meadows in the Rocky Mountains of Colorado (Ives, 1942). Extensive wet meadows were attributed to inheritance from former beaver lakes. Ives suggested that the infill sedimentation was characterised by a sedimentary architecture possessing a variant on the classic Gilbert-type delta with top, foreset and bottom set units. This mechanism was seen to be the dominant process of alluviation, rather than simply the infill of former glacial lakes. Ives was also aware that changing climate had previously enabled beavers to create meadows in areas that are currently beyond the limits of tree growth due to increased aridity; in these he claimed to be able to identify buried beaver dams.

Apparently unaware of the conclusions of Ruedemann and Ives, almost 30 years later, a Dutch geologist Martin Rutten observed that braided rivers were not restricted to periglacial environments but were also common in Mediterranean climates. But he observed that typically Alpine glaciated valley floors are much flatter than those due to braided river deposition alone. He also noted that braided rivers in Iceland and the Mediterranean were comparable in cross profile roughness. Thus he proposed that flat-bottomed Alpine-type valley floors could not be simply a product of braided river process nor a periglacial climate. An additional geomorphological agent was required - the beaver (Rutten, 1967). As European

***Figure 11**. A beaver lodge in swampy terrain at the inflow end of the beaver lake at Old Chelsea in Québec (map, Figure 9). Mud is plastered on the outside of the lodge, the food cache is adjacent, and beaver-excavated canals connect the lodge with the main lake.*

valley floors had long been settled and cultivated, the drainage networks were channelled artificially; hence he argued that an examination of natural river systems in areas such as displayed by the Bow and Columbia rivers in the Canadian Rockies might provide a better analogue for the former European alpine natural rivers. There, as expected, the floodplain marshes were heavily colonised by beavers. 'A beaver inhabited glacial valley is consequently characterised by horizontal, marshy bottoms, wherever its longitudinal gradient becomes so low that beavers are able to pond up the streams, separated by rapids of the braided river type where the gradient is stronger' (p357). Rutten augmented his analysis by comparing air photographs from Iceland and the Mediterranean (non-beaver areas) with the upper Columbia River in the Rocky Mountain trench where beavers are ubiquitous. In a postscript, he acknowledged that after submission of his paper he had been alerted to the pioneering paper by Ruedemann and Schoonmaker.

In assessing these conclusions, it is pertinent to recall that even today in North America beaver population levels are estimated to be only one tenth of those that prevailed before European human colonisation. Hence it is necessary to extrapolate by about an order of magnitude the contemporary scale of landscape modification due to beaver activity in order to gain a true appreciation of the role of beavers in geological processes in the modern valley floor sedimentary environment. It follows that there is a strong possibility that a similar conclusion could be applicable to Europe, at least in the early post-glacial prior to significant human modification of the landscape. It is salutary to consider this factor in the context of the Holocene floodplain sedimentary record.

Beaver lithostratigraphy in Britain

River Kennet case study, southern England

The notion that beavers *per se* might have influenced sedimentation in valley floodplains can be traced back at least to 1867. In that year, the Wiltshire Archaeological and Natural History Society convened a meeting in Hungerford, Berkshire. Two papers were presented and each independently suggested that the peats and calcareous marls (tufa) that occur extensively beneath the floodplain of the lower River Kennet might reflect wetland environments created by beavers' dam-building activity. The association of peat and beavers

***Figure 12**. The same lodge as shown in Figure 11, but 3 months later in the grip of winter. Unlike most of the year, winter affords the opportunity to walk up to the lodge – note the snow shoe prints in the left foreground.*

***Figure 13**. Ventilation hole in the summit of the lodge seen in Figure 12. Even at temperatures of -20ºC, the snow directly above the hole has melted, indicating that the body heat from the beaver family within the lodge below is sufficient to maintain a clear air passage, though hoar frost crystals have formed around the rim of the hole.*

was linked to the common occurrence of sub-fossil beaver bones within the peat along with material of other species and a range of Neolithic and Bronze Age artifacts. The discovery of these finds was due mainly to an extractive industry that required the hand digging of peat, which was in operation from before 1700 until about 1870. The peat was dried for fuel and also burned on site to yield ashes that were in demand as a fertilizer. A consequence of the extraction is that the floodplain landscape is heavily influenced by peat extraction, and at one locality the main Kennet river channel switches across its 'floodplain' on an embankment some 3 m above the adjacent fields.

A Rev John Adams of Stockcross (a parish northwest of Newbury) perceptively outlined the geology of the Kennet and stated 'may we not owe the peat of the Kennet valley in great measure to obstructions to the natural drainage caused by beaver's dams?' (Adams, 1869). In addition, Dr Silas Palmer (1878, p132) asserted 'The Beaver has been an effective agent in altering the conditions of river-valleys by his dams and weirs, and thus leading to the subsequent growth of peat, and often flooding and prostrating the forests in such valleys'. The next significant contribution was that of Harold Peake in his presidential address to the Newbury District Field Club in 1935. After reviewing all the previous literature pertaining to Kennet beavers, he claimed that their relict dams could still be identified in the floodplain landscape at Marsh Benham just west of Newbury and in the centre of Newbury town (Peake, 1935). Finally, Coles (2006) has suggested that unexplained 'trenches', revealed in earlier archaeological excavations at Thatcham and Newbury, might be relict beaver-dug canals. Surprisingly, when the area was mapped by the Geological Survey c1900, the origin of the peat was not addressed (White, 1907) and the same comment applies to the recent resurvey's explanation of the geological map (Aldiss *et al,* 2006).

A conundrum arising from the conclusions to John Wymer's Thatcham excavations relates to the concept that the low terrace bluff (on which most of the Mesolithic site was located) overlooked a lake; 'what is now a reed swamp is presumed to have been a stretch of clear water, probably a narrow lake' (Wymer, 1962 p336). It is suspected that comparisons with the roughly contemporaneous Star Carr led to the assumption that a lake must also have existed at Thatcham. Despite being a minor component, the presence of beaver in the fauna would have undoubtedly encouraged this thinking. Yet the allied geological study (Churchill, 1962) of the sequence in an open pit, dug through the modern reed swamp, revealed, below a surface peat, a bed of 'algal marl' consisting of sphaeroidal calcium carbonate concretions. In current terminology this is tufa, and Churchill made it clear that from his own observations that it forms in slow-flowing, shallow, hard, freshwater streams. Gravel was extracted from Thatcham Reedbeds below the Holocene floodplain and close to the excavation site in the 1970-80s, and this involved stripping surficial peats and tufa. Sections clearly indicated that the area had previously been dug for peat and that only a thin basal sequence remained, implying that the present day geomorphology reflects an abandoned mining landscape.

The presence of beavers, and parallels with Star Carr have led the archaeological community to favour a lake shore palaeo-environment. Cornwall (1969, p127) expressed the view that the presence of a thick calcareous marl 'certainly indicated a lake and a long phase of open water with a minimum of vegetation, for the material contained very little organic matter'. He enthusiastically asserted that there had been at least 2-3 m of 'deep water' forming a 'very extensive' lake. He attributed to F.E. Zeuner the suggestion that a beaver dam downstream towards Reading was responsible for the lake (perhaps he had read Peake, 1935!). Another

Figure 14*. River Kennet floodplain stratigraphy, as exposed at the Thatcham Reedbeds in the mid 1970s, when the pre-Holocene gravels were being worked for aggregate after the cover of Holocene tufa and peat had been stripped away.*

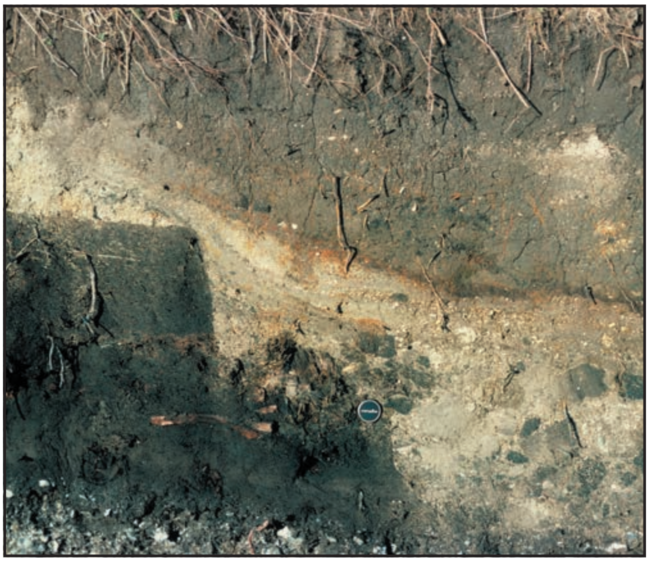

Figure 15. Section at the Thatcham Reedbeds showing a nearly vertical termination of the peat bed on the left. To the right, banked against the peat, is a complex of redeposited tufa and peat clasts that constitute an unlithified breccia. This section is interpreted as the limit to a former peat extraction site, with subsequent flooding and deposition in the old workings. This site lies within 250 m of the classical Mesolithic settlement site of John Wymer.

worker supporting a beaver created lake at Thatcham is Evans (1975, p88), who considered that a lake was hard to explain solely on local topographic grounds. Yet despite this euphoria, the marl (or calcareous mud) is derived from tufa produced by an endothermic precipitation reaction in slow flowing water, a process especially active during warmer summer conditions; *i.e.*, it signifies a river channel rather than a lake environment *per se*, (Collins *et al.* 2005). It appears that, in the Holocene, the Kennet floodplain was a dynamic network of channels, localised pools and swamps - a perfect beaver habitat. A complex of Holocene peats (= swamps) and tufas (= fluvial channels) accumulated across the floodplain and lapped onto the marginal terrace. Alas, any surviving dams remain elusive.

East Lincolnshire marsh

A possible example of an East Midlands site influenced by beavers occurs at Aby Grange on the east Lincolnshire marsh (NGR TF430798). This locality was investigated in one of the early papers that integrated palaeoecology and radiocarbon dating of late glacial deposits to establish the age of the last deglaciation of the east coast (Suggate & West, 1959). An irregularly shaped depression in till less than 1 km across was found to be capped by an extensive mottled silty clay. Auger holes and ditch sections showed that this clay overlies a late glacial sequence restricted to a small basin, the latter feature of possible kettle hole origin, being the focus of the study. However, the surface silty clay unit was 'interpreted as a rapidly accumulated deposit in a lake' and 'probably began … after a rapid rise in water level established a lake over the whole of the depression' (p265). Such a lake must have been controlled by the lowest point on the bounding perimeter at about 14 m OD. No further comment on the lake was made by the authors, as it was clearly postglacial in age and not relevant to their investigation. The mechanism for the flooding remains unresolved, but the field relations are such that it may be due to beaver dam activity.

Conclusion

It is clear that the effects of beavers on alluvial stratigraphy have been largely unappreciated. This is understandable in those areas that suffered beaver extinction some centuries ago. However, even in regions where beavers are common, the lessons that their presence ought to stimulate in the minds of physical geologists are often overlooked. The importance of beavers in influencing geological processes in floodplain environments is normally omitted in textbooks on fluvial geomorphology and sedimentology; this is to the detriment of a fuller and more realistic understanding of fluvial environmental change in the Holocene in particular.

The value of beaver dams in regulating stream flows, especially at times of high run-off, is rarely comprehended. In effect, the natural environment of those temperate regions currently lacking beaver because of overkill extinction are out of equilibrium with the longer term norm solely due to short-sighted human behaviour. An interesting question is whether the catastrophic impact of the flooding in parts of southern

Figure 16. *A beaver lake that has become a part of the landscape in the Canadian Yukon, with new shrub growth on the dam long abandoned by the beavers that built it.*

Figure 17. *Beaver at work in Alaska.*

England over July 19-20, 2007, would have been ameliorated if beavers still inhabited the floodplains. There is no doubt that beaver works check erosion and maintain the local water table, and on the longer timescale beaver meadows are a valuable resource for wildlife, grazing and cultivation.

Acknowledgements

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MEMBERS' EVENING 2009

The third Members' Evening was held on 14th March 2009, when the theme was volcanoes. 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.

Volcanoes of Chile

Alan Filmer

Chile's past and present are inextricably tied to the subduction zone in the Pacific Ocean that runs down the length of the South American coast. Subduction of the Nazca Plate in the north and the Antarctic Plate in the extreme south, both sliding beneath the South American Continent, has been continuing since before the break up of Gondwanaland during the Jurassic. There is therefore a wide age range of rocks uplifted by the orogenesis to form the Coastal Range, which rises to over 4000 m in the north of the country but is lower further south. In the north the coastal mountains are mineralised and produce Chile's most valuable exports, copper and silver. These mountains also prevent many of the northern rivers from the Andes from reaching the sea, the water evaporating in the Central Depression between the Andes and the Coastal Range - where evaporites are exploited for lithium and boron salts. Further south the Central Depression forms the Central Valley around the capital, Santiago de Chile. There the climate is lovely, and Chile's fruit and vineyards thrive. Still further south, the Depression forms the Chilean Lake District, which, in spite of its annual rainfall of over 4 m, is a popular tourist destination.

Inland from the Central Depression, the Andes rise to 6800 m to form a volcanic mountain chain for the length of the country, that is 5000 km long on the borders with Bolivia and Argentine. The most striking volcanoes are of Pleistocene or Holocene age and many have near perfect cones. Of these, 250 are active. Those in the far north rise from the Altiplano, a high plain at 4500 m above sea level or the Atacama Desert at 3000 m. Here rain is rare or unknown, and the volcanoes are easily seen. Further south in the Lake District the volcanoes are lower and rise from temperate rain forests at around 1000 m, and they are usually hidden by cloud.

Parinacota and its debris avalanche on the Altiplano.

In the north of Chile the extreme aridity of the continent results in almost no supply of sediment to the subduction trench. So rather than the usual accretionary process, subduction causes erosion of the continental margin - which has retreated east by about 250 km within the last 25 Ma. The descending slab of oceanic crust rasps the underside of the continent, occasionally breaking pieces off, to generate deep-seated earthquakes. Shallow earthquakes result from movements along the numerous north-south trending faults within the continental plate.

Arica is the most northern Chilean coastal city and although only 17º south of the equator may be quite cold. It has not rained in Arica for over 100 years though it is often foggy. A good road leads inland, over the Coastal Range to the small town of Putre. At 3500 m altitude, this is a good place to acclimatise before continuing up to the Altiplano at 4500 m, most of which is in Bolivia. The small Chilean section is designated the Lauca National Park, with its abundance of wildlife, thermal springs and impressive volcanoes. These include Parinacota and its spectacular 8000 year old debris avalanche (Waltham, 2004).

The town of Putre, built on a pyroclastic flow 2000 years old from Taapaca.

The crust here is said to be the thickest on Earth at about 70 km. Above the Benioff Zone, the subducted Nazca plate is boiling off the sea water that is taken down in the subducted plate, and this aids the melting of the rocks at the base of the continent to form magma. There is a small contribution from the mantle and from oceanic sediment taken down on the plate. The magma incorporates more continental rock as it rises, so eruptions are highly explosive and produce mainly andesitic ash and lavas.

The small tourist town of San Pedro de Atacama is 600 km to the south and gives access to the great salt flats, also to both the Andes and the inland sides of the Coastal Range (Filmer, 2008). Nearby are the volcanoes of Licancabur and Lascar; the latter is Chile's most active, with 26 eruptions since 1900. Access for visitors is not easy, but the very scenic twin lakes and volcanoes of Miscanti and Miniques are easily reached.

The Lake District, 2500 km further south is a very different, verdant and very watery world. Most of its volcanoes rise to about 3000 m, with the intervening lakes at about 1000 m. Many are in National Parks or have developed ski facilities, so have easy access, but others such as Llaima and Chaiten (both of which were erupting in 2008) are more remote.

The beautiful cone of Osorno in the Lake District.

Charles Darwin in Chile

In 1834-5 Darwin was travelling on HMS Beagle when it was engaged in surveying the coasts of Argentina and Chile. He took every opportunity to go ashore, and spent over a year in total making several expeditions across the Coastal ranges and into the Andes. He examined the volcanic and metamorphic rocks and studied Cretaceous ammonites. He was particularly struck by finding marine shells on mountain tops. While in the Lake District he witnessed Osorno erupting, and ashore at Valdiva he felt an earthquake. Twelve days later HMS Beagle reached Talcahuano, the port serving the city of Concepcion. Darwin was horror-struck at the total devastation of the coastal settlements and port by the tsunami that had followed the earthquake, and found there was not a stone building left standing in the city. He also noticed that the coastline had been raised by several feet. Surprisingly the death toll was less than 100 and Darwin recorded many eye-witness accounts of events. The inhabitants had been pre-warned by seeing great flocks of birds flying inland, by tides occurring at the wrong times, by smoke seen rising from the sea and by the sight of a great whirlpool. When the town's dogs all set off for the hills, the people knew it was time to follow. Darwin also learned that several volcanoes along a 1000 km length of the Andes had erupted two days after the earthquake. The local people knew that all these events were connected, but Darwin was the first to write a scientific account that clearly connected all the events to movements in the Earth's crust, thus giving support to Charles Lyell's revolutionary, uniformitarian ideas about crustal evolution, uplift and erosion.

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The lake and volcano of Miscanti, near the oasis town of San Pedro de Atacama.

Volcanoes of Northern Tanzania

Gerard and Brenda Slavin

The volcanoes in northern Tanzania have developed in association with the Eastern Rift Valley. The Rift, which is about 50 km wide in Kenya, diverges into a zone 200 km wide zone with three different orientations through Tanzania. Early faulting in the Neogene produced a tectonic depression in Tanzania, limited to the southeast by the Pangani graben and to the southwest by the Eyasi half graben, each influenced by basement structures. Faulting was accompanied by large shield volcanoes. These, the Older Extrusives (>1.2 Ma), are mainly alkaline basalts with flows that filled and extended beyond the depression. No outcrop is seen where lavas overlie basement rocks, and the earliest dated, a nephelinite on Essimingor, is 8.1 Ma.

Major faulting, at 1.2 - 0.9 Ma, formed the modern north-south Rift in the centre of the older depression. Unlike the narrow graben in Kenya, the central Rift in Tanzania is a half graben with a steep east facing escarpment from the Kenya border, southwards through the Natron, Engaruka and Manyara basins. The floor of older lavas, is broken by tilted fault blocks, horsts and grabens. Faulting was accompanied by explosive Younger Extrusive volcanoes (<1.2 Ma) which are mainly ultrabasic/ultra-alkaline and are accompanied by carbonatites. Pyroclastics and lavas form major volcanoes with steep profiles, and eruption activity continues. Minor volcanic features are widespread.

Arusha to the escarpment

A journey from Arusha to Oldoinyo Lengai starts westwards across a faulted terrain, climbing steep scarps and descending dip slopes towards the escarpment, passing to the north the Younger Extrusive volcanoes, Monduli and Burko; many small tuff cones are asymmetrical because of prevailing east winds. Some are basaltic scoria cones, but others (such as Lashaine rising 200 m above the plain south of Monduli) are carbonatite tuffs with basement and mantle xenoliths. Travelling northwest, Essimingor, the oldest volcano in Tanzania is passed: in the east it has the sharp upstanding outlines of a strato-volcano; to the west, breach of a crater permitted extensive lava flows to emerge with smooth profiles. A further descent leads to the foot of the escarpment with the Manyara basin to the south and the Engaruka and Natron basins to the north. The escarpment here shows faulting through basaltic lava flows from the Older Extrusives of the Crater Highlands to the west.

Looking south along the Rift wall towards Lake Manyara. The nearest buttresses are basalts of the Crater Highlands.

Ketumbeine, an Older Extrusive shield volcano seen from the west. The lower slopes are basaltic lavas, with more viscous trachyandesites and trachytes on the upper slopes; the flat top is due to caldera collapse.

North along the escarpment

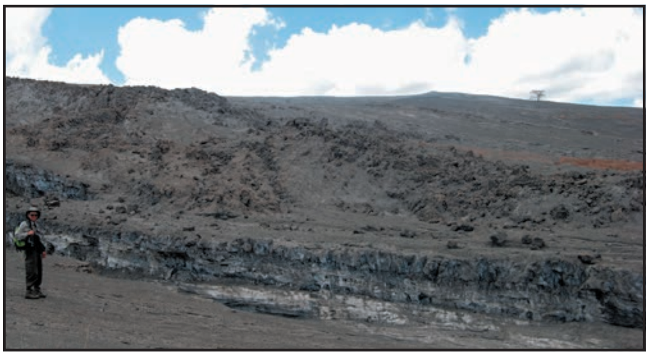
Northwards, the single unsegmented scarp 250-500 m high separates the highly faulted Engaruka block from the Engaruka Basin. This is separated from the Natron Basin by a horst block bordered on the east by the Older Extrusives, with Gelai and Ketumbeine with its distinctive profile, and the Younger Extrusives, with Kerimasi and Oldoinyo Lengai, to the west. The escarpment runs close to Kerimasi and disappears beneath that mountain, buried by nephelinite and carbonatite tuffs from the now inactive volcano, before reappearing close to Oldoinyo Lengai.

The horst block is disturbed by minor volcanic features. There are many tuff cones with greater deposition of tephra to the northwest due to prevailing winds close to the escarpment. Loolmurwak is one of

Kerimasi, a Recent Extrusive volcano seen from the southeast, with pyroclastics overstepping the Rift wall..

Oldoinyo Lengai, looking south from Lake Natron. The white weathering of carbonatites near the summit was misinterpreted as snow in the nineteenth century.

A rainwater gully cuts through bedded carbonatite lapilli tuffs and pyroclastics on the flank of Oldoinyo Lengai. The broken ridge just beyond is aa lava from the 2006 eruption.



many maars, explosion craters rimmed by tuff rings with gently graded outer slopes and vertical inner walls of bedded pyroclastics, which originated when magma came into contact with seasonal surface and subsurface waters. Relationships of the tuff cones to dated debris flows from Oldoinyo Lengai indicate ages of about 2500 years. Many are oriented NNW-SSE, corresponding to faults on the lower slopes of Kerimasi and Ketumbeine.

Oldoinyo Lengai

Close to the escarpment, Oldoinyo Lengai is a classic volcanic cone rising 2090 m above the surrounding plain and dominating the southern Natron Basin. It is the only active carbonatite volcano in the world. Initial phonolitic and nephelinitic tuff deposition began at about 0.37 Ma, with subsequent lava flows from the southern crater. After an inactive period, erosion and slope instability produced massive debris flows to the north and east; those to the east and north of Oldoinyo Lengai extend 16 km across the Natron Basin and form islands in Lake Natron.

Activity from the northern crater began about 125,000 years ago, when nephelinite tuffs and lavas were interbedded with natrocarbonatite flows and ashes. In the 20th century, carbonatite lavas and ashes predominated. Major lava surges in the crater in 2006, fed lava flows down the western slopes. From September 2007, sporadic Vesuvian and Plinian activity continued until April 2008, with widespread airfall ash and fine tephra. The crater is now filled with a major ash cone.

The inner wall of the Loolmurwak maar. The pale lower pyroclastics came from Kerimasi, and through these Loolmurwak erupted with a base surge that deposited the dark tuff with festooned bedding up to the crater rim.

At the col between Oldoinyo Lengai and the escarpment, recent pyroclastics including ash and lapilli tuff were deposited around a lava flow of March 2006. This lava consisted mainly of thick blocky aa and thinner pahoehoe lobes, with a pale grey/whitish exterior colour but black on freshly broken surfaces. These changes are due to the chemistry of the lavas. Natro-carbonatites are unique to Oldoinyo Lengai and the anhydrous lavas contain phenocrysts of the complex Na-K-Ca carbonates nyerereite and gregoryite. These are jet black on extrusion but reaction with atmospheric moisture leads to formation of simpler carbonates and sylvite, with greying of the aa lavas and whitening of the pahoehoe. The white weathering of carbonatites near the summit was misinterpreted in the past. On an 1855 map of East Africa, Oldoinyo Lengai was classified as a "Snow Mountain" together with Mount Kenya and Kilimanjaro.

Magmatism of Northern Tanzania since 1.2 Ma contrasts with that of southern Kenya's Rift Valley, where activity consists largely of extrusive trachytes. This change occurs at about 2º S, and may reflect rifting through contrasting rocks of the Tanzanian Craton and the Neoproterozoic Mozambique fold belt in Kenya.

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We thank Prof. Barry Dawson who led our tour and who, in 1960, when working for the Tanganyika Geological Survey, was the first to descend into the active northern crater.

Mud Volcanoes of Azerbaijan

Tony Waltham

Azerbaijan is a small but rather splendid country where the fold mountains of the Caucasus break through semi-desert lowlands and disappear beneath the Caspian Sea. As a nation it receives very few leisure visitors, but the geologically inclined tourist may well be drawn to its mud volcanoes. The Absheron Peninsula, adjacent to Baku, is host to a plethora of geological activity, with water, oil, gas and mud seeping to the surface through the thick pile of sediments in the Caspian basin.

Baku was in the forefront of the world's oil industry back in the 1870s, when it was matching Pennsylvania in its development. The city now stands at the heart of a second boom based on the vast oilfields of the Caspian, and the new oil provides wealth and supports industry on a grand scale in today's Azerbaijan. Oilfields surround the city, but the most important are now out into the Caspian, where platforms dot the horizon. On land, and notably out on the Absheron Peninsula, the oilfields provide some amazing industrial landscapes. There are nodding donkeys galore, slowly dragging the oil up into a network of pipelines. But the finest panoramas are of the forests of tall drilling derricks in the Ramana oilfield, east of Baku, which are reminiscent of the well-known scenes photographed on Signal Hill in Los Angeles back in the 1930s.

Surface oil seeps were recorded by Marco Polo, and are what started the exploitation boom in the 1800s. Many are still active today, and evaporation of the volatiles leaves material more akin to tar as sticky black crusts floating on ponds of rusty water that also emerges from the ground. Elsewhere, methane emerges and spontaneously ignites. The natural fires east of Baku were some of the prime sites of fire-worship in the origins of the Zoroastrian religion, but vents change over time, and most of these sites are now dead. Yanar Dag, near the Ramana oilfield, is a hillside of roaring flames popular with local people as somewhere to take tea on a cool evening.

Flames of methane on the burning hillside of Yanar Dag.

Azerbaijan has more than 400 mud volcanoes, including many on the floor of the Caspian Sea; these add up to about 70% of the world's total. The mud is mainly sourced from mid-Tertiary organic shales at depths as much as 8 km, and is largely separate from the oilfield reservoir rocks at shallower depths. Faults along anticlines, associated with the Caucasus disturbance, appear to offer the mud the necessary routes to the surface. Azeri mud volcanoes come in all shapes and sizes. Many of the smaller features (with dimensions of tens of metres) are in states of almost continuous activity, with conical edifices, advancing mudflows, growing mud domes or muddy pools on their vents. Emerging gas creates delightful bubbling mud pools on some of the vents. Many mud flows mimic the textures of lavas, notably ropey pahoehoe on the smaller scale. The mud-water ratios, the rates of extrusion and the subsequent evaporation rates determine the viscosities of the mud flows and hence the profiles of the mud volcano cones. Individual vents are typically subsidiary features on larger mud volcanoes, kilometres across and hundreds of metres high, and comparable to parasitic vents on basaltic shield volcanoes.

A forest of drilling derricks in the Ramana oilfield that is still producing on the Absheron Peninsula.

Along the Caspian coastline, south of Baku, the Firuz crater lies on a broad low shield south of Gobustan, with easy access via a long dirt road; there are numerous active adjacent vents, and lines of broken baked mudstone where flames of methane once emerged. West of Baku, the Perekishqul shield is also capped by a fine collection of active mud vents and short mudflows. Less accessible is Turagay, a massive mud volcano over 400 m high, with a shallow caldera in its gently rounded summit dome and all its flanks scored by deep rainwater gullies. Between Baku and Gobustan, Lokbatan is a splendid mud volcano rising over 100 m, with oil derricks littered across its flanks. From its summit a mud flow extends for nearly two kilometres, with splendid arcuate pressure ridges that are comparable to those on some obsidian flows; this is now totally dry, but Lokbatan means "the place where camels get stuck". Its upper zone is littered with blocks of baked mud that were hurled out of its vent during the eruption of October 2000. That event was marked by methane flames that reached 300 m high for about five minutes, before settling down to flames of just 15 m for a few days. This was a fantastic sight, but was only one of various methane explosions that have been recorded around Baku within historical times. Though these outbursts are rarities, at least some of the mud volcanoes are always active, and they make a short visit to Azerbaijan geologically memorable.

A small flow of viscous mud from a vent on the mud volcano of Perekishqul.

Very fluid mud flowing from an active vent on a mud volcano near Gobustan.

The extensive mudflows that emerged from Lokbatan in October 2000; note the person on the left for scale.

REPORT

Nottingham's Castle Rock

Castle Rock is doomed to disappear. That is of course in the geological long-term. As an upstanding block of relatively weak rock, the ravages of natural erosion will eventually see it off. In the short-term, it is still with us, though weathering and degradation of the rock faces are inevitable processes. So Nottingham Council aims to keep its iconic Rock in good shape, and a swathe of engineering works were initiated over the last winter.

In years gone by, there had been a philosophy that a good covering of soil and vegetation on the Rock was generally beneficial, with the leaf cover shedding the rain and a root mat holding it all together. This also appealed to the bio-conservationists who liked greenery, and to the City Treasurer who could cut down on the cost of clearance work. But that approach was not the best. Whereas a good root mat gives stability to a soil, by offering tensile strength and also better drainage, the same roots do little but harm to rock.

Once roots are into rock fractures, they just keep on growing, forcing the blocks of intact rock apart and significantly reducing the strength and stability of the rock mass. Individual blocks are heaved off exposed faces and fall to the base, where they form a ramp of talus unless regularly cleared away. Or, ivy can do the damage and then hold the blocks unseen in its mantle until they fall off at random times. The root impact is best seen in the caves in Castle Rock. Each joint has tiny rootlets, and a few have much larger roots, hanging down. Bedding in the Rock's sandstone is hardly visible in a clean face, but almost all the rock actually has distinct bedding planes at intervals of about 10 or 20 mm, and the finest roots are surprisingly effective at working along these weaknesses. The result is bedding plane failure in the cave roof spans; some of the caves just behind the rock face on Castle Road have this on a massive scale. And what is visible in the caves is also happening unseen on almost all the Rock's faces.

So the current stabilisation works started with a major clearance of the vegetation. Some of the larger trees have been taken down because their roots were reaching far into the rock; shrubs that had established in open joints and fissures are being removed; and the great screens of hanging ivy have been cut away. At the foot of the Rock at the corner into Peveril Drive, the holly trees have been removed as their roots were breaking down the roof of the nearby Water Cave. Two large trees on the Castle Boulevard lawns have also been removed, but a single tall ash tree has been retained at the wish of the planners because it is a native species, though it now looks rather out of place. A side effect of all this has been a huge improvement in the appearance of Castle Rock. Especially round its southern end, west of Brewhouse Yard, it is once again a bold geological feature, instead of just another blob of urban greenery. The Nottingham Castle Sandstone has regained its type locality back from the holly and the ivy.

A cover of soil and low plants is kept on the upper slopes that lie back at lower angles, and one of the main challenges for the contractors has been to manage and control this boundary between soil cover and bare rock along the crests of the main faces. Once cleared of vegetation, the works follow on with repairs to the rock. Judicious concreting and reinforced plastic coating is under way where needed, notably sealing the main fissures where roots deep inside cannot be removed but must be prevented from re-growth. Rock repairs are almost invisible where loose sand is rubbed by hand over the cement or plastic before it has gone hard, to create a good "sandstone" surface. A careful search reveals where this has been done, but most casual observers just do not see most of this critical repair work. This will include repairs within the caves, including the Western Passages which it is hoped can soon be re-opened to extend the tours through Mortimer's Hole, creating the loop tour that was so popular some years ago.

The follow-up work on the Rock is going to centre on trimming back the ever-creeping vegetation. This will be done, by rope-access workers swinging across the rock faces, perhaps once every two or three years, in what should be a declining task once the vegetation is more continuously under control. Then Castle Rock should survive a little longer as the Nottingham landmark that we all know.

Tony Waltham

The newly cleaned south end of Castle Rock, as seen from Castle Boulevard.

REPORT

Nag's Head Caves, Nottingham

Fronting onto the Mansfield Road, north of the city centre, the Nag's Head has a splendid set of cellar caves cut into the local sandstone, consistent with the many other caves beneath the city. These were somehow missed from early surveys, but that has now been remedied, at least with a reasonable map of the site. The Nag's Head caves are more extensive than beneath most inns in Nottingham, and are also unusual by way of their multiple levels.

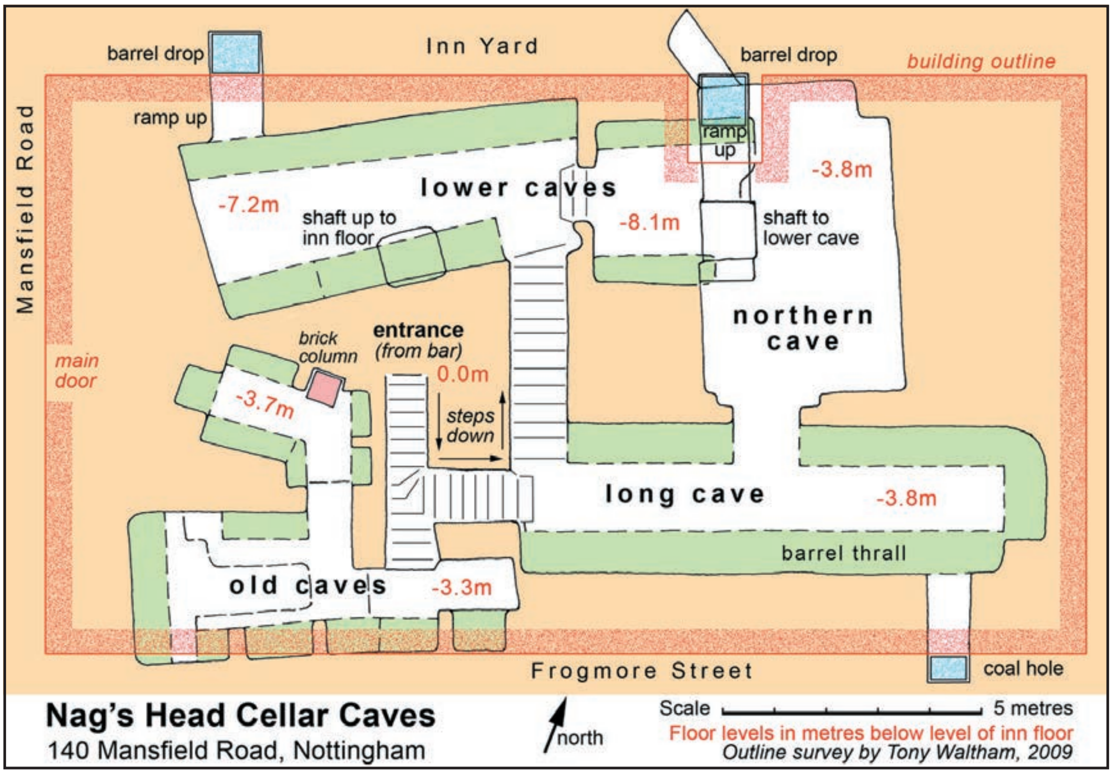
Straight down the entrance steps, the set of smaller caves are clearly the oldest, and lie beneath the footprint of the oldest part of the building, which is believed to date back over 250 years. The long cave is clearly a larger and later addition, which extends beyond the footprint of the old building. This lies beneath a building extension that post-dates maps from the 1860s. It appears that all the later caves pre-date the building extension, as the main barrel drop, through the northern cave and into the lower cave, would have been outside the contemporary building. The original vertical shaft was modified with a steep ramp to reach the inn yard in a recess within the later building. Both this and the second barrel drop, straight into the lower cave and also inclined to reach the yard, are now capped beneath new paving. An internal shaft from the lower cave is also capped by the bar floor. What appears to be a coal hole, opening high in the long cave wall, is also capped by recent paving.

All the caves have gently arched rock ceilings at the conventional height of about 1.9 m high, except the northern of the old caves, with its roof at about 1.7 m. From the recorded floor levels (on the map) most of the cave roof arches lie just under 2 m beneath the inn floor. It appears that the inn buildings were set slightly into the sloping ground so that little or none of this thickness is weathered and weakened material; the roof of the entrance steps exposes 1.3 m of good solid sandstone. The lower cave has 2.3 m of rock separating it from the small part of the northern cave that lies above it.

There are stories that the caves were used to house condemned prisoners who were allowed a last ale on their way from the town jail, before heading to the gallows, which were in use into the 1800s, at the top of the hill. But the many barrel thralls suggest a different concept, and it is more likely that the last drinks were taken outside to the passing prisoners. It appears that the caves are just another set, but a very fine set, of beer cellars.

Tony Waltham

The long cave that lies at shallow depth beneath the rear of the Nag's Head, with the entry arch into the northern cave on the left.



Outline plan survey of the cave cellars beneath the Nag's Head public house.

REPORT

Rock fall at Bridgnorth cave

In April of this year, slabs of rock fell away from the roof of a sandstone cave at Bridgnorth, killing a teenage boy who was sleeping below. This tragic accident has implications for the East Midlands as the cave is very similar to those that lie under and around Nottingham.

Bridgnorth has many caves, all of which are entirely artificial and were cut into the low cliffs of soft red sandstone centuries ago; details of the original reasons for their excavation are lost in the mists of time. There are at least 60 caves within High Town, on the west side of the River Severn.

The rock fall was in one of the Hermitage Caves, a group of about 20 in the hills on the east side of the Severn, above Low Town. These have been cut into the Permian Bridgnorth Sandstone, a red, aeolian, dune-bedded rock, but some rise into the overlying, fluvial Kidderminster Conglomerate that straddles the Permo-Triassic boundary. The sandstone appears to be slightly weaker than Nottingham's rock (though the conglomerate is stronger). Comparisons of roof failures in the Bridgnorth and Nottingham caves would therefore appear to be valid with the proviso that the rocks are not identical but only broadly similar.

Processes behind the fall of roof rock in the Bridgnorth cave were multiple. The cave is only a small rock shelter reaching back about 5 m from the vertical cliff face. Natural stress relief within the entire outcrop will have allowed micro-fractures to open up within the rock, which has conspicuous bedding planes but relatively few joints through the beds. The cave has been exposed to weathering for some hundreds of years, in which time any fractures would have further developed and the sandstone would have weakened by softening of its natural cement. It may be significant that the summer of 2008 was very wet and was followed by a hard winter with many frosts, perhaps weakening the cave rock even further prior to April 2009.

Two of the Hermitage Caves, in the dune-bedded Bridgnorth Sandstone with the Kidderminster Conglomerate above.

Aftermath of the roof fall in the Hermitage cave (photo: AP).

A critical factor in the roof fall appears to have been the fire that the teenagers had built in the cave when they decided to camp there for the night. Flames were reported to have reached over two metres high, which would have taken them right to the cave roof; it was nearly 2 am when the roof fell, by which time the flames would have significantly heated the rock. The blocks that fell were from a bed over 100 mm thick; a block "the size of a suitcase" landed on the chest of the sleeping boy. He stood no chance, and a nearby girl was also injured. The cave rock fall was therefore a simple case of artificially induced thermal weathering, whereby the roof rock was heated and expanded so that it separated from the cooler and unexpanded rock above it. Pre-existing bedding planes within the rock, already opened by natural weathering and stress relief, would have acted as foci for this separation, and it was unfortunate that their wide spacing allowed such large blocks to fall away.

Falls of large blocks are rare in the Nottingham caves, where roof sandstone in tension tends to split into beds only about 10 mm thick; this commonly happens where the rock is saturated by a broken pipeline, but the Bridgnorth rock was not saturated and did not delaminate. Tree roots are know to be very destructive in the Nottingham caves, where they reach into the thinnest of bedding planes and fractures, there to grow and expand and eventually heave away blocks of the sandstone. They have also been seen to damage some caves at Bridgnorth, but do not appear to have been significant at the Hermitage cave site, as none is seen on the new fracture surfaces exposed by the roof fall.

The rock fall at Bridgnorth appears to have been a very sad accident. It has no implications for the stability of caves in either Bridgnorth or Nottingham, except for the clear evidence that it is unwise to build a fire inside any cave. Fire-splitting was a standard method of excavation in all types of rock before explosives were available; without a fire, these sandstone caves are very stable.

Tony Waltham and Christine Rayner

REPORT

Great Fen Project

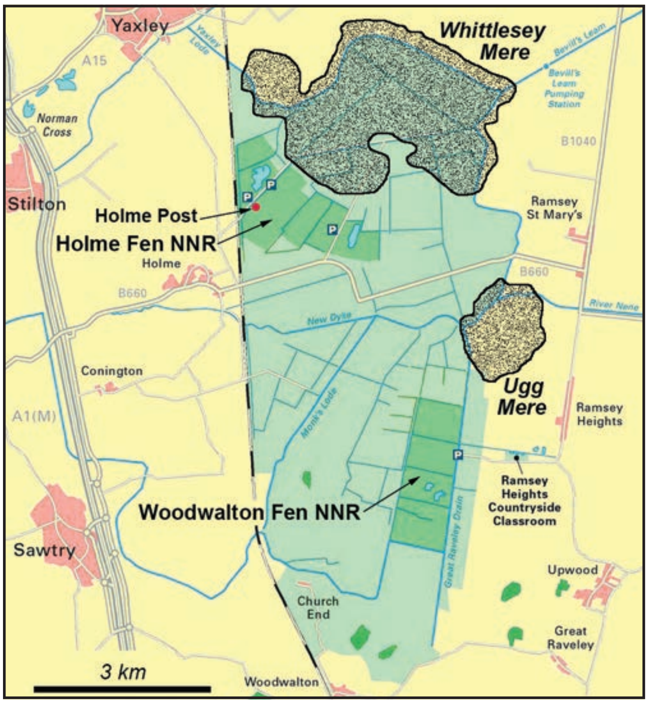
On the eastern fringes of the East Midlands, the wide expanses of the peat-floored fenlands are among the most distinctive and unusual of Britain's geological and landscape sites. The fens were great natural wetlands until about 500 years ago, but almost the whole area has been progressively turned into productive farmland, totally destroying a piece of England's natural environment. Now the Great Fen Project aims to reverse the process and turn a small part back to its original wetland state.

The plan is to re-create 3700 ha of fenland, mainly from land that is currently under arable farming. The chosen slice lies midway between Peterborough and Huntingdon; it includes two small National Nature Reserves that are currently unsustainable because their water tables are falling when managed solely for the benefit of the surrounding farmland. Across the new Great Fen, pumped drainage will cease and the land will be managed as a wetland, though some control will be needed to prevent undue long-term flooding of areas that have subsided from their original positions (much is now below sea level). The result will be to re-establish a very special part of Britain's ancient natural landscapes.

The project has mainly botanical values, as it will safeguard many unique plant species, but there are major geological benefits too in conserving a piece of one of the world's classic peat terrains. The Great Fen Project has a planned budget that exceeds £5M, which is mainly for land acquisition and its subsequent management; there is more data in the project's website at www.greatfen.org.uk .

Originally, the fens were huge wetlands of meandering rivers, raised bogs, birch woodlands, reed beds and grasslands. Beneath was the outcrop of the weak Oxford Clay, but the wealth of plant material preserved under water had created the peat that then nurtured the fen environment. But nature was forestalled in the early 1600s when the first of the fens were drained to turn them into valuable agricultural land. This was a long process, and it was 1850 when the last of the fen lakes, Whittlesey Mere was drained; this had been the largest lake in lowland England, though it was only about a metre deep when it was finally eliminated.

An unwelcome side-effect of the fen drainage was to cause extensive land subsidence, due firstly to compression of the drained peat, and then to wastage of the newly dried ground. Wastage is simple oxidation of the dry peat, so that it is lost to the atmosphere; this incidentally adds to atmospheric carbon dioxide, with whatever effect that has on global climates; the converse is achieved by conservation of the peat with its positive impact on the nation's carbon budget. Under the current drainage regime, peat loss is around 15 mm per year - a figure that is entirely controlled by the climatic mean temperature and the depth to the water table. The classic record of peat loss is provided by the Holme Post (see the *Mercian Geologist* for 2000), which stands inside the Great Fen's confines; there is now only about 2.5 m of peat at the Post, way down from the original 6.7 m.



Outline map of the Great Fen, with the conservation area shown by the light shading (after the Project's own map); the extents of the two original Meres are also indicated, as they were before their complete draining.

The Great Fen Project is certainly bold, and should be hailed as an ambitious piece of environmental conservation. There are those who question its worth, expressing concerns over the loss of farmland at a time when food prices are rising. But the drained peat will eventually be lost anyway, due to the inevitable process of wastage. And when the peat has gone, the land will revert to an expanse of relatively barren soils on the clay that will be exposed from beneath. The total area of peat within the English fens is already down to less than half the area of its ancestral wetlands. A small slice preserved as the Great Fen would seem to be an appropriate use of land in a rapidly changing world.

Tony Waltham

REPORT

Nottingham Natural History Museum, recent developments at Wollaton Hall

At Easter, 2007, Wollaton Hall reopened for visitors every day of the week, following 18 months of restoration and refurbishing work, costing around £9M. As well as extensive repairs to the building's stonework, the Prospect Room above the Great Hall was completely restored, a new café was created in the Courtyard Buildings and a lift, new toilets and new displays were installed in Wollaton Hall. Some of the new displays were about the history of Wollaton Hall and the people who have lived there over the years and others were about the natural history collections. The latter group included a new display in the Bird Room and a new display on the first floor called Natural Connections.

A wide variety of fossils and taxidermicly prepared animals are on display in Natural Connections. The fossils range from crinoids, trilobites and corals from the mid-Silurian through to a giant deer's skull and antlers on open display and bones and teeth of mammals like wolves, bears, hyena and woolly rhinoceros from the Pleistocene deposits in the caves at Creswell Crags and other Nottinghamshire localities. There is also a pallasite meteorite and a small number of rocks, minerals and pressed plants.

However, you can still see the best of the museum's mineral collections in the Minerals Gallery, also on the first floor of the museum in Wollaton Hall. The main theme behind Natural Connections is an illustration of the wide variety of life that exists on Earth today and also did so within the geological past. Many of the fossils are brought to life with an artist's reconstruction of what the animal or plant might have looked like when it was alive.

Another theme is a selection of people's choices of particular animals or fossils, rocks or minerals on display with an explanation of what connection they have with their chosen object through a video and a label. For example, the writer's personal choice is of a seed-fern frond fossil, *Mariopteris sp*., that was found in Hucknall Colliery, Nottinghamshire. It was chosen, not only because it is undeniably attractive, but also because it represents the museum's very strong collection of Coal Measures plant fossils from the Nottinghamshire and North Derbyshire coalfield, which include some scientifically important fossils collected from collieries that have long since closed. Other people's choices include a part of a fossil tree discovered by Tony Waltham and his students when the A610 Eastwood by-pass was being built, a Cambrian trilobite (*Hydrocephalus sp.*) from the Czech Republic chosen by Bob Kennedy a trilobite researcher, and a *Chirotherium* footprint found in the Mapperley area of Nottingham and chosen by a local student.

The fossil frond of Mariopteris *from Hucknall Colliery.*

This February, to mark the bi-centenary of Charles Darwin's birth, some animals were newly restored by our taxidermists, including a maned three-toed sloth, a giant anteater and a duck-billed platypus. These have been added to the Natural Connections display, and tours of the gallery were given to highlight certain fossils, rocks, minerals and animals on display that had connections with Darwin's life and works.

Other areas of current work include updating the details of, and answering enquiries about, the Regionally Important Geological Sites (RIGS) in Nottinghamshire and co-operation with others in the local RIGS group to help conserve and promote the County's important geology sites. The databases of the museum's geology collections, and the care of the collections, are being constantly improved. The museum has a free public enquiry service, and attempts to answer any queries about geological specimens. Recent calls have been about fluorite specimens from Crich in Derbyshire.

The Nottingham Natural History Museum is open from 11am to 5pm from April to October (last entry 4.30pm) and from 11am to 4pm from November to March (last entry 3.30pm). Entry to the Museum and to Wollaton Hall is free. The museum can be viewed on the Nottingham City Council website: http://www.nottinghamcity.gov.uk (click on *leisure and culture* then *museums and galleries* and under *Wollaton Hall, gardens and deer park* select *Natural History Museum*). Geological enquiries can be sent to neilt@ncmg.org.uk or made by phone at 0115 915 3907 or 3900.

Neil S. Turner
Keeper of Geology, Wollaton Hall

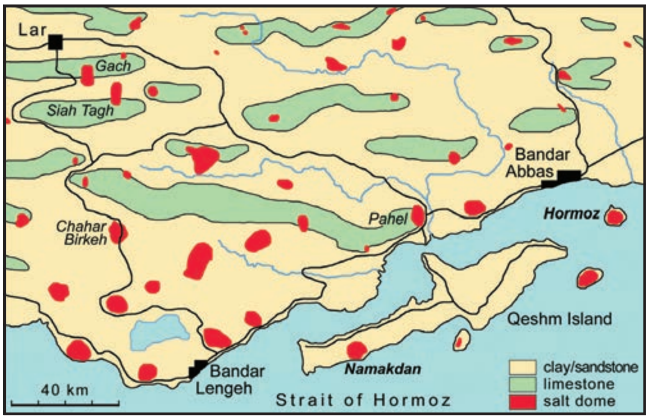
LECTURE

Salt terrains of Iran

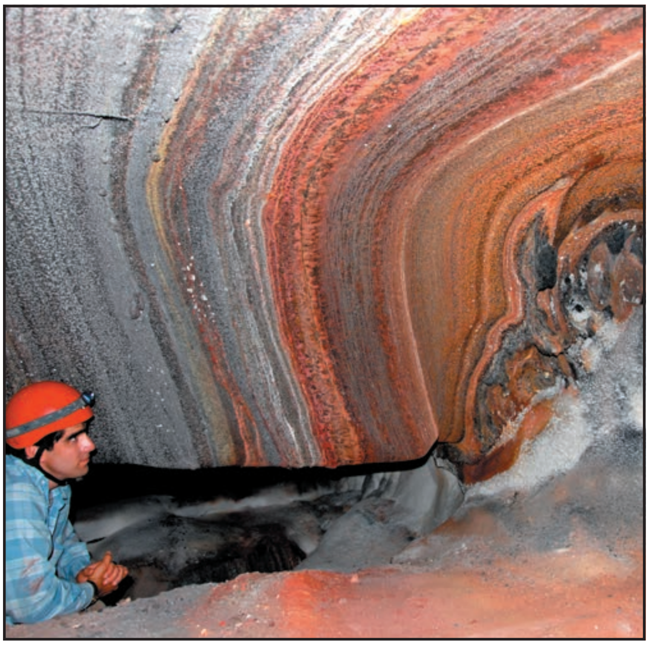
A lecture given to the Society on Saturday 13th December 2009 by Dr Tony Waltham, Editor of the Society's Mercian Geologist.

The 130 salt domes in the southern Zagros are eroded into some of the world's finest landscapes of salt karst, and they also contain the world's longest and largest caves in salt. Beneath most of the Persian Gulf region, the kilometre-thick bed of Hormoz Salt lies at depths of 4-10 km, but it has also been mobilised into diapirs that intrude its cover rocks and reach the surface in more that 200 salt domes. In the desert climates of the region, with about 170 mm of annual rainfall in the coastal regions, the salt survives at outcrop.

Compared to nearly all other rocks, salt is extremely soft and mobile, so it flows as diapirs that intrude through other rocks on a scale only matched by molten magma in igneous intrusions. The driving force behind diapirs is the positive buoyancy of salt because its density is so much lower than that of other lithified rocks. At depths of 5 km or more, the huge overburden pressure is enough to squeeze the salt into any weakness in the same overburden rocks. The movement commonly starts with some fault displacements, but once established a diapir can push its way up through any cover of much stronger sedimentary rocks. Many of the Zagros salt diapirs rise through the anticlines of cover rocks, for which the Zagros are justly famous, but the anticlines probably grew by lateral compression of an initial fold created by the salt diapir.



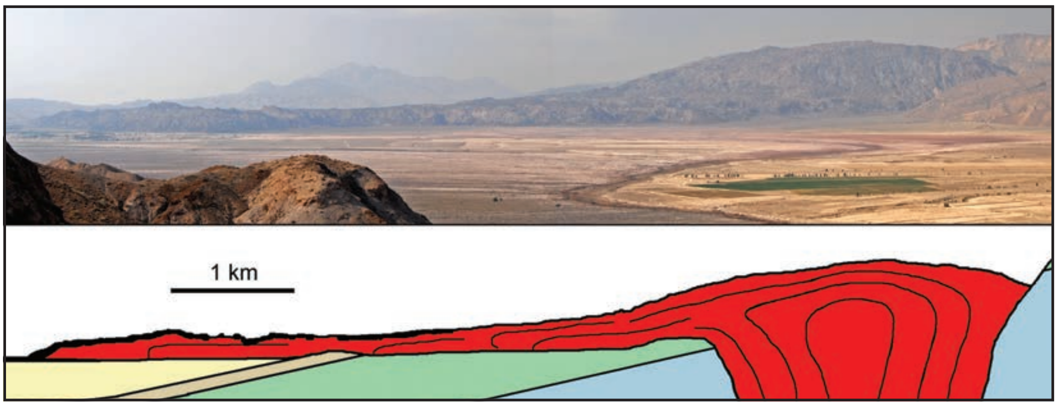
Geology of the coastal Zagros Mountains around Bandar Abbas.



Almost vertical banding within the salt, with some flow folding on the right, exposed in the roof of Fatima Cave, within the salt dome of Hormoz Island.

Domes and glaciers of salt

When the rate of diapiric uplift exceeds the mean rate of dissolutional loss beneath soil cover in the desert regimes, the salt rises to form domes that stand hundreds of metres above the surrounding countryside. Most of the domes are 1-10 km across, and their great domed mountains have bare outcrops of white salt that gleam in the sunlight, though much of their surfaces are masked by red soils. The main caprock soil, generally some metres thick, is a residuum of the insoluble components from within the original salt beds. This is dominated by clays and silts, but commonly contains up to 50% gypsum. The red colour is derived from up to 15% iron oxides, mainly in the form of earthy hematite, but there is abundant black specularite on some domes. The cover rocks are commonly upturned around the edges of the domes, with some remnants extending up onto the salt outcrops. The existence of these mountains of salt requires that their underlying diapirs are still rising. Typical uplift rates for those in the Zagros are 2-6 mm/year, though some appear to be growing at up to 15 mm/year.



The Gach salt glacier; seen from the west in a photograph taken from on the Siah Tagh glacier, and drawn in a sketch section.

Rugged terrain near the northern margin of the Hormoz salt dome, with doline karst well deveoped in the soil cover over the cavernous salt.

Where diapiric uplift far exceeds surface erosion, the excess of salt becomes unstable as a high dome, and flows away as a salt glacier. With morphologies somewhere between ice glaciers and lava flows, salt glaciers are extruded from rising salt domes, to simply flow at mean rates of a few metres per year down into an adjacent synclinal valley. They can reach lengths of 5 km or more, with widths typically of a few kilometres between steep margins that stand 100 m high. Each glacier advances in a tank-track motion, rolling over itself as the salt is deformed into recumbent folds; analogies are drawn with alpine nappe systems. Unlike in an ice glacier, there is no basal shear, and a better comparison is drawn with an aa lava flow with its hot core advancing over cooled rubble. The salt glaciers of Gach and Siah Tagh, near Lar, are fine examples. Their surfaces are mantled by thick residual soil that is carved into badland topography of steep gullies and sharp ridges with little exposed salt. Dolines are recognisable on some glaciers, and small streams emerge from the toes of some, but karst landforms are subordinate to those produced by the glacier movement.

Flow rates have been estimated and measured on salt glaciers around Bushehr (far to the west of Bandar Abbas) by Chris Talbot and colleagues from Uppsala and Shiraz universities. Mean flow rate appears to be around 2 m/year, though old maps indicate that the front of the Kuh-e-Jahani salt glacier has advanced about 200 m within 25 years.

Karst and caves in the salt

Even in the deserts of Iran there is enough rainfall to create spectacular karst topography on the highly soluble salt. Karst landforms are best developed on the stable salt domes, and are especially splendid on the coastal salt domes of Namakdan and Hormoz, where they have been well documented by Czech geologists led by Pavel Bosak. The net effect of dome denudation is to create spectacular doline karst. At the kilometre scale this is polygonal, with networks of interfluves around closed depressions that each drain into a central sinkhole or cave. Etched into the polygonal relief are thousands of closely packed dolines, each 5-30 m across. Most of these are partly or largely formed within the red caprock soils, but they reach downwards into open shafts or choked sinks within bedrock salt. Rapid dissolution of the underlying salt creates areas of spectacular instability where the soils are actively collapsing into open voids on a scale that makes just walking across the land distinctly exciting. All stream courses that emerge from caves appear as streaks of white across the landscape, where the brine has deposited thick crusts of sparkling white salt crystals.

Beneath the red soils and the doline karst, cave passages carry the ephemeral drainage through the solid salt. To date, just a few have been explored and mapped by the Czech geologists. Their finest discovery has been the Tri Nahacu Cave has more than 6 km of passages, many of them more than 5 m high and wide, reaching

Bedrock salt with a thick soil cover, exposed beside a stream channel that is floored with crystalline salt on the Hormoz Island salt dome.

between a sink and a resurgence that lie 2 km apart in the Namakdan salt dome. Though the cave is almost entirely of Holocene origin, the rapid salt dissolution has already allowed it to evolve to an almost perfectly graded profile; it descends steeply from the sink, but then has only a very gentle gradient right through to its resurgence. Between large chambers and spacious galleries, there are low sections of passage where silt and clay sediments have accumulated to levels less than a metre below the roof. With salt dissolution concentrated at the water table (above the denser brine), many of these passages are now up to 50 m wide. Some chambers have broken roof profiles left by block collapse, but others have smooth arched profiles created by granular disintegration of the coarsely crystalline salt. These salt caves are still very active, and large blocks of bedrock salt fall from their ceilings at a frequency far greater than the very rare cave roof failures in limestone.

The caves are also remarkable for their abundance of beautiful, pure white, salt decorations. Dominant are thick stalactites up to 4 m long. Most of these are curved, because they formed as lattices of salt crystals that could grow away from the vertical, before gathering overgrowths that gave them their smoother final profiles. There are also clusters of long thin straw stalactites, again made of salt, each with a diameter little more than that of a drinking straw. These are remarkable for their overgrowths of tiny helictites that twist away in all directions, again the product of randomly orientated crystal growth.

All these snow-white deposits of crystalline salt are exceptionally beautiful, and these splendid decorated caves beneath the ground complement the spectacular surface landforms to place the salt domes of Iran among the more remarkable and unusual geological terrains known anywhere in the world.

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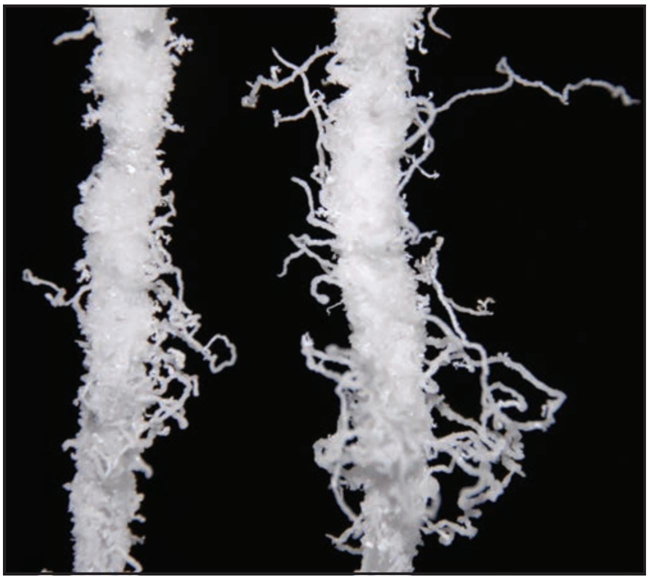


Helictites on salt straws in one of the smaller caves in the Namakdan dome; the two vertical straw are each about 4 mm in diameter, and the helictites growing from them are very thin and very fragile.

A small chamber along an old cave passage within the Namakdan dome, with a profusion of salt crystals and stalactites growing down from its ceiling.

REPORT

The Crags of Sutton Knoll, Suffolk

The SSSI at Sutton Knoll (TM305441), also known as Rockhall Wood, southeast of Woodbridge, reveals excellent exposures of a fascinating aspect of the Neogene Crags of East Anglia. Here the Coralline Crag, about 3.75 Ma in age, forms an upstanding hill, while the later Red Crag, about 2.5 Ma in age, can be seen lapping over the Coralline Crag around the sides of the inlier. Prestwich (1871a,b) is the classic description, while Boswell (1928) wrote the Geological Survey memoir of the Woodbridge area. Later descriptions are given by Balson and Long (1988), Balson *et al* (1990), Balson (1999) and Wood (2000), and Dixon (2006, 2007) describes recent developments. Balson *et al* (1993) describes the stratigraphy of the Coralline Crag as a whole. The Coralline and Red Crags are the lowest two of the four formations within the Crag Group, the Red Crag being succeeded by the Norwich Crag and finally the Wroxham Crag (Hamblin *et al* 1997, Hamblin 2001).

The site was visited by the Society on September 1st 2007, during a day's excursion led by Roger Dixon and Peter Norton. At that time, members of the GeoSuffolk society, led by their conservation officer, horticulturalist Barry Hall, were in the process of cleaning up the site, and an explanatory panel was planned. In appreciation of Roger's and Peter's efforts that day the EMGS offered to fund this panel, and the completed panel was unveiled at a ceremony on May 14th 2009. Bob Markham, chairman of GeoSuffolk, gave a brief talk on early workers at the site, which has been studied for over 170 years, and Roger Dixon, treasurer of GeoSuffolk, explained his own researches. Guy and Jenny Quilter, owners of the Sutton Hall Estate, were in attendance, and Jenny Quilter unveiled the panel. Roger Dixon also showed us a painting of the site as it would have appeared in Red Crag times, painted by A-level art student Louis Wood, and this could well be used in a future explanatory panel.

After the ceremony, Roger Dixon led a walk around the site exposures. These reveal the Ramsholt and Sudbourne members of the Coralline Crag Formation, and the overlapping Red Crag Formation. The London Clay lies at shallow depth but is not now exposed. The visible exposures are mostly old pits dug to extract Coralline Crag to improve and repair farm tracks. One pit had been dug in 1860 to extract phosphate nodules commercially from a bed at the very base of the Coralline Crag where it overlies the London Clay, but this was not economical and the pit was filled in 1862. The GeoSuffolk explanatory panel has been placed at the northeast end of the site so that it may be read by walkers on the adjacent public footpath. Behind the panel, steep faces of bioclastic sands, at the top of the Ramsholt Member and base of the Sudbourne Member, show current bedding that indicates a derivation from the north.

The Bullockyard Pit was cleared by Natural England in 2006 and has been cleaned up further by GeoSuffolk, to expose a length of over 13 m of the wave-cut platform by which the Red Crag Formation overlies the Ramsholt Member. This surface dips southwards and small blocks of Sudbourne Member Rock Bed can be seen resting upon it, within the Red Crag. The surface is difficult to see because of the quantity of

The panel, produced by Elizabeth Hall.

Painting by art student Louis Wood showing the sea floor at the time of the Red Crag transgression.

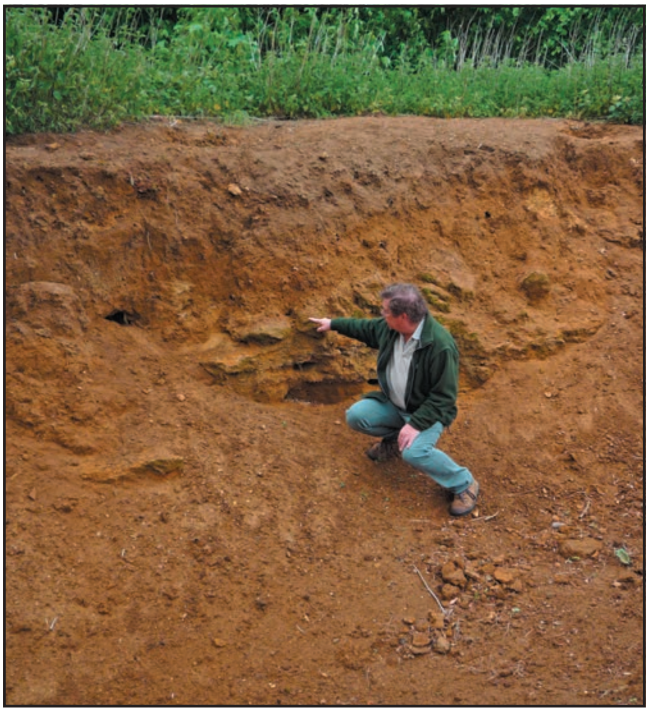
derived Coralline Crag material in the Red Crag, but colonies of *Mytilus edulis* are found at the base of the Red Crag. The valves are articulated and closed and the full range from juvenile to adult are present, and since this is typically an intertidal rocky shore species, the communities are clearly in their life positions, attaching themselves to the wave-cut platform in between loose blocks of Rock Bed. The Red Crag was formed in a high-energy shallow sea with strong tidal currents, dominated by molluscan shell assemblages indicating a climate similar to the present day, while assemblages in the underlying Ramsholt Member indicate a warmer, Mediterranean climate. Shell-beds here indicate larger, more robust bivalves including *Arctica, Cardita, Pecten,* and Britain's largest fossil brachiopod, *Terebratula grandis*, implying strong currents.

The Chicken Pit at the western end of the site also reveals blocks of Rock Bed at the base of the Red Crag, again with colonies of *Mytilus,* but in this case the blocks are much larger boulders, up to 1.5 m in length, interspersed with pockets of relatively clean sand with perfectly preserved bivalve shells. Barnacles encrusting blocks of Rock Bed show that this was fully lithified by the time of the Red Crag deposition. At one side of the Chicken Pit, excavations have revealed the Red Crag resting directly upon the London Clay, a surface heavily bored by the bivalve *Zirfaea crispate.* The absence of the Ramsholt Member at this point reminds us that at the time of the Red Crag transgression, the site was an isolated hill outlier of Coralline Crag surrounded by a flat terrain of London Clay.

The panel unveiled: left to right, Bob Markham, Roger Dixon, Barry Hall, Jenny Quilter.

The Quarry Pit was not visited on the occasion of the unveiling, but was seen by EMGS members in 2007, where about 5 m of shelly sands of the Sudbourne Member are exposed. These sands are calcite-cemented to form the relatively durable Rock Bed, significantly more resistant than the underlying Ramsholt Member and accounting for the upstanding mass of Sutton Knoll. Post-depositional solution has dissolved the aragonite of the bivalve shells and precipitated this as calcite to bind the rock, and clearly this happened before the Red Crag transgression since blocks of this rock are found lying on the Red Crag beach. The Rock Bed has been used locally as a building stone.

Sutton Knoll is a great tribute to GeoSuffolk. It is an important site and has been expertly cleaned and described. The Coralline and Red Crag formations form an important part of the relatively recent history of Britain, and since these formations are so easily eroded, we should have few sites to look at if it were not for the efforts of such societies. For any reader of *Mercian Geologist* who fancies a holiday in Suffolk, a visit to Sutton Knoll is strongly recommended; the hand-out produced for us by Roger Dixon in 2007 is still available, and has been very useful in writing this account. Although the site lies beside a public footpath and the explanatory panel can be read from the footpath,



The exposure in Bullockyard Pit shows Red Crag that rests on a wave-cut platform cut in the Ramsholt Member; Roger Dixon points to blocks of Rock Bed resting on the platform.

the site itself is privately owned by the Quilters and potential visitors planning access to the pits are advised to approach GeoSuffolk via their website. A visit could readily be linked with a visit to the important ship-burial archaeological site at Sutton Hoo, which lies between Sutton Knoll and Woodbridge and is now expertly managed by the National Trust. Go to Sutton Hoo in the morning, because if you go to Sutton Knoll first then you will get so absorbed that you will miss the guided tour at Sutton Hoo in the afternoon, as we did. Have lunch at the Ramsholt Arms on the banks of the River Deben, then go to Sutton Knoll. Finally, on your way home, buy some sausages from Five Winds Farm butchers at Melton railway station, they are amazing!

Acknowledgements

Thanks are due to GeoSuffolk, in particular Roger Dixon, Bob Markham and Barry Hall, for their sterling efforts in cleaning up and describing the site, to Barry's daughter Elizabeth Hall for her work on producing the explanatory panel, and to GeoSuffolk secretary Caroline Markham for organising the unveiling ceremony and making the sandwiches. Guy and Jenny Quilter are thanked for providing access to the site.

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Richard Hamblin

REVIEWS

Castleton Caves by Trevor Ford, 2008. Landmark Publishing: Ashbourne. 128 pages, 64 photos, 47 maps, 978-1-84306-406-0, £9.99.

Across all the splendid limestone landscapes of the "White Peak", there is a remarkable shortage of open or known caves. But the small area between Rushup Edge and Castleton provides the redeeming exception, as these limestone hills are riddled with long, large, deep and truly spectacular caves. And few people can know these caves better than the author of this rather fine book. Its pages contain descriptions of all the caves, along with a plethora of maps and surveys, significant sections on the geology and geomorphology, and a 32-page section of very fine colour photographs mainly by Paul Deakin.

The book is aimed at both the active caver and also the interested surface dweller who may venture into the show caves and want to know more about what really exists inside Castleton's limestone hills. With such a double target, the book could fall between the two stools, but it successfully avoids doing that because it is packed with so much interesting material. So that's good. But the reader does have to work at his study. With too little correlation between the text and the numerous maps, with many localities referred to in the text but not appearing on maps, and with a lack of sub-headings, the reader may find it hard to follow his thread. Perhaps the author knew the caves too well to really look after the slightly lost reader. Problems arise because many of the maps are historical items, which pre-date further explorations and are therefore incomplete. Careful captions could have avoided this issue and made more of the historical story. Peak Cavern starts on page 15, but the first complete map is on page 28.

Despite these problems, the book is welcome. The large chunk of it describing the Peak and Speedwell caves is enthralling reading. Few can unfold the story better than Trevor; he was after all at the sharp end of some of the explorations in Speedwell (many years ago now), and he has the mining knowledge to link it all to the miners who were into so many of the passages before the cavers. Then his chapter (with welcome sub-headings) on the evolution of the caves, before and through the Pleistocene, will give any geologist or geomorphologist food for thought.

For the non-caving member of the Society and for many others, this book will bring to attention a whole new world of geology and geomorphology that exists, has evolved and is studied within the ground. At the symbolic penny less than £10, the book is very good value. It has to be a winner for anyone who enjoys the natural world of the Peak District.

Tony Waltham

Lithostratigraphical framework for Carboniferous successions of Great Britain (Onshore) by C N Waters, M A E Browne, M T Dean and J H Powell, 2007. British Geological Survey Research Report RR/07/01. 60 pages, 9 large figures, 14 tables, 9780-85272-603-7, from http://www.bgs.ac.uk/downloads/home.html as a free download.

The British Carboniferous has long been of great economic importance and intense academic research interest, and this important work of reference is a timely summary of how the rock sequences are subdivided and related to each other. Correlation of the various lithological units across multiple sedimentary basins and contrasting palaeo-environments has been the major task over a number of years of a number of Stratigraphic Framework Committees at BGS, and this is their Report.

After briefly describing the tectonic setting, palaeogeography and principle lithofacies of the rock succession, the text sets out the way by which it is divided into Groups, Formations and Members. There then follows the main meat of the Report, which is a description of all twenty six Groups that have been accepted as meaningful and useful subdivisions by the Committee. Reference to the appendices shows that these Groups are made up of no less than 187 Formations, many of which are also briefly described in the running text. No doubt there will be a few geologists who will be upset when they discover that the name of their favourite Group or Formation has been rejected in favour of another name, but this process of rationalisation is a necessary aid to clarity in the reviewer's opinion.

As is usually the case, a disadvantage of the 'report', as opposed the 'book', form is that there is no index – something that would have been very useful in a work of reference such as this. To some extent, this is made up for by providing separate chapters for each of five regions and then providing a separate description for each and every Group within those regions. Helpful text figures show stratigraphic columns for various parts of each region together with the main lithofacies (in colour) and chronostratigraphy. Thus, for example, it can be seen in Figure 6 that the Urswick Limestone Formation is part of the Great Scar Limestone Group of Asbian age in the Visean and is of platform/ramp carbonate facies.

This document is never going to be bedtime reading, but it is a very important piece of work that must be referred to by anyone working in or just interested in the Carboniferous rocks of our home area; and providing it as a free download is a refreshing approach by BGS towards the dissemination of valuable information.

Neil Aitkenhead

Granite and Grit: a Walker`s Guide to the Geology of British Mountains by Ronald Turnbull, 2009. Francis Lincoln: London. 208 pages, 250 figures, 978-0-7112-2914-3, £20.

Brenda and I have a fatal disease - we just cannot walk past a bookshop. Our latest acquisition is *Granite and Grit*, which despite its name has a splendid photograph of a limestone pavement at Scales Moor below Ingleborough on the jacket.

Ronald Turnbull is a geographer, climber and hill walker. He has written an account of the geology that underlies British mountains, mainly those over 600 m. It has been written as an introduction to geology for those with some knowledge of the subject, but who have been stimulated by days on the hills and wish to know more about the rocks.

A brief introduction to the tectonics of Britain through the ages, and the role of glaciation in shaping mountain landscapes, is followed by accounts of each mountain group roughly in a north-south sequence. Mr Turnbull`s style is clear and simple, but not simplistic. Basic geological concepts are explained with lucid diagrams that will greatly help beginners. Descriptions of the mountains are supported by the many colour photographs, and these are the great attraction of the book. Most are excellent and evocative of days out on the hills (but why did he use such a cramped picture of Buchaille Etive Mor instead of the classic view from Kingshouse?). However, with this attraction there has to be a "health warning" for the beginner, because the author is not a professional geologist and there are some gaffes in the text. To name but three: he places the Millstone Grit above the Coal Measures (p21); he cites the origin of the Great Whin Sill as "the area about Arthurs Seat" (p142) and he asserts that quartz veining in rocks is due to molten quartz boiling out of magma, as "often as not from subjacent granite" (p54).

Running through the book is a light vein of the history of British geology. James Hutton is found in connection with Siccar Point, Salisbury Crags and Glen Tilt, within an account of the vigorous Plutonists v Neptunists debate. The Southern Uplands are illustrated by Charles Lapworth's work on graptolites at Dobb`s Linn. Adam Sedgwick appears several times (although once as Alan), as does Charles Darwin, while Roderick Impey Murchison is dismissed as "not very likeable".

At first reading I sat entranced by the photographs, retracing my steps over favourite hills - Langdale, Glencoe, Torridon and on and on - but with new nuggets of geology thrown in on almost every page. And there is stimulation for the future: why have I not yet visited the Rhinogs? Why didn`t I follow the Rosset Ghyll fault in its entirety? This is a book to enjoy on cold winter evenings with a glass of Laphroaig beside a warm fire. It will entertain and inform, but read the text critically. And at £20 it is a bargain for the photos alone.

Gerard Slavin

Minerals of Britain and Ireland by A.G. Tindle, 2008. Terra Publishing: Harpenden. 624 pages, 978-1-903544-22-8, £95.

This is a beautifully produced alphabetical listing of all the 2200 reported mineral species, varieties and synonyms in the British Isles, including discredited and fraudulent records. It has over 500 stunning photographs, mostly in colour, that complement the excellent text, which is fully referenced with over 1500 entries. Each mineral is described, with the type locality if it is in the British Isles and biographical details of any British or Irish citizen after whom any mineral is named. The locations, generally mines, of the localities from which each mineral has been described are listed by country, county and region in alphabetical order. Details, including grid references or maps, of the localities are not given. There is also an overview of the mineralisation of the British Isles with a set of generalised colour maps showing the more important localities. Numerous minerals are found in Derbyshire, but other parts of the East Midlands also feature.

Nothing like this has been produced for 150 years, and it amply justifies the widespread anticipation of amateur and professional mineralogists and collectors, some of whom have been in correspondence with Andy Tindle for some years to provide information. It has been 14 years in the making and has been lovingly and carefully put together. Errors are very few despite the comprehensive coverage of this very detailed subject.

This is a large (624 pages) and heavy (clay-rich pages to take the high quality images) specialist publication, but the sumptuous appearance of the book, along with the superb illustrations, should widen its appeal to the more general reader. An extended sample, with example pages and illustrations is on the publisher's website at http://www.terrajr.demon.co.uk/mbisampler.pdf .

Tim Colman

A Geological Excursion Guide to Rum by C.H. Emeleus and V.R. Troll, 2008. Edinburgh Geological Society. 150 pages, 77 figures, 978-1-905267-22-4, £12.99 (at www.nms.ac.uk/books).

This guide enhances and replaces the Nature Conservancy's field guide on the "Tertiary Igneous Rocks of Rhum" and the booklet "Geological Walks on the Isle of Rum". The first authors on those publications are now the joint authors of this new guide, for their research has focussed on Rum for many years. Dr Emeleus is the author of the BGS Memoir on Rum and the Regional Geology on Palaeogene igneous Scotland.

An introduction of 23 pages summarises the geology of Rum, with the classic references and others as recent as 2007, so the visitor can do the homework beforehand. It then describes nine excursions with geological features at 107 locations, with numerous, quality colour photographs, many annotated. Each excursion is shown on a small solid geology map. The first five excursions include Kinloch, the Northern Marginal Zone, the Eastern Layered Intrusion, the Central Layered Intrusion and the Harris Bay area as well as the Canna Lava Formation (as in "Geological Walks on the Isle of Rum"). The others cover Minishal in northwest Rum, with the Southern Mountain Group and Glen Dibidil. Emphasis is on Palaeocene igneous rocks, so Mesozoic, Torridonian and Lewisian rocks are only mentioned where relevant to the igneous rocks.

The guide is also truly practical, with good advice on getting to Rum and staying in the Castle, a tent or a bothy. All routes are described with distances, times and potential hazards; alternative routes find easier ground or avoid streams in spate. The guide is beautifully produced on glossy paper with a waterproof semi-rigid cover, and fits easily into a pocket. I used this guide for a week in June 2009; it is robust and survived heavy rain and rough handling in the field.

The book is a credit to the authors and to the publishers, Edinburgh Geological Society in conjunction with the National Museums of Scotland. For a visit to Rum it is indispensible, and is remarkably well priced.

Gerard Slavin

The Earth After Us by Jan Zalasiewicz, 2008. Oxford University Press. 978-0-19-921497-6, 251 pages, £14.99.

Food for thought: 100 million years in the future, Earth is visited by aliens with investigative geological skills and knowledge - what residual evidence will they find of the brief geological period when *Homo sapiens* was present and the even briefer period when his industrial and agricultural revolutions made widespread changes? Dr Zalasiewicz, a palaeontologist and stratigrapher at Leicester University, poses the question. He then takes us through the findings he expects the aliens to make, as they communicate in animated whispering within a ravine in the great North Continent, after discovering evidence of our unusual anthropogenic stratum sandwiched between sandstones and shales.

Nothing will remain of our urban infrastructure on the surface, but coastal regions with subsiding basins will have the best potential for fossilisation, and the structural complexes of foundations, tunnels and conduits with their bricks, concrete, wires and plastics will all be available for preservation. Here is a sample: "One may predict a range of fossilised plastic bottles along the Urban Strata, varying in colour from pale yellow to brown to black, depending how deeply they were buried. Other plastics might, under heat and pressure, breakdown completely into their component molecules......to become a minute fraction of newly forming oil and gas reserves." Alien palynologists will have a field day noting the changes that followed the development of agriculture, especially where selective strains were bred and exported around a world with a paucity of native pollens, a process that the author terms the "McDonaldisation" of life. Of ourselves there will be little direct fossil evidence. The possibilities of a human Lagerstatten are few, but you never know!

This is a thought-provoking book that covers a lot of ground in a popular science format that is easily accessible without being simplistic. I enjoyed it.

Gerard Slavin