MERCIAN Geologist

The Journal of the East Midlands
Geological Society

Volume 18 Part 1 August 2012

MERCIAN Geologist

VOLUME 18 PART 1 AUGUST 2012

East Midlands Geological Society

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Mercian Geologist is printed by John Browns, and published by the East Midlands Geological Society.

ISSN 0025 990X

Front cover: The apron reef limestones of Parkhouse Hill, formed on the edge of the Carboniferous Derbyshire Carbonate Platform, and visited on a Society excursion (see p80). Photo by Tony Waltham.

Back cover: Gypsum extraction from the upper part of the Mercia Mudstone at the opencast pit of Bantycock Mine, at Balderton, south of Newark. Photos by David Bate and Tony Waltham.

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The geological setting of the lead mines of the Hucklow, Eyam, Stoney Middleton and Longstone Edge area, Derbyshire by Trevor D Ford

PROFILE

Brian Jones

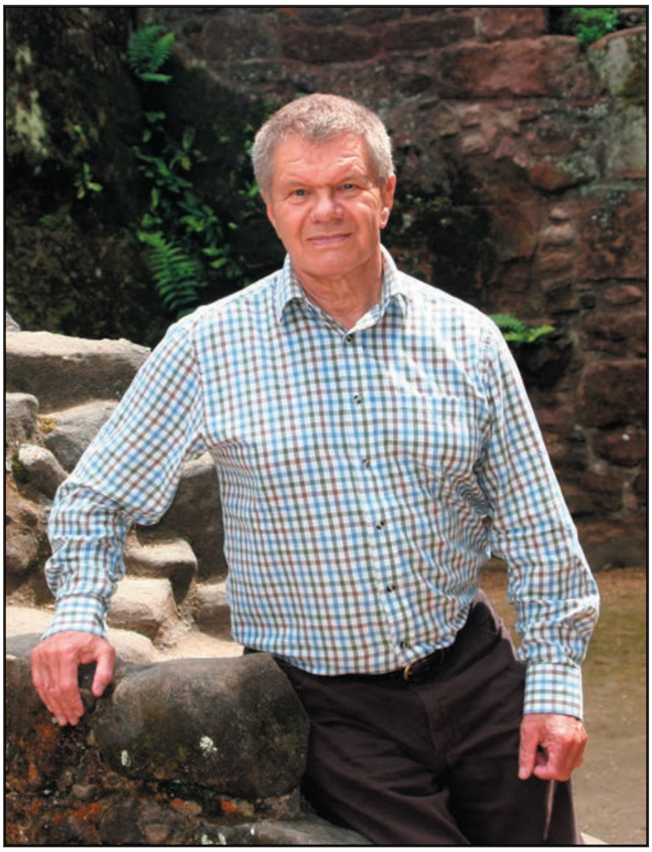
Our new president, Brian, was born in the suburbs of Nottingham early in the Second World War, and was brought up largely by his mother, with his father serving in the army. Leaving school at the age of 15, he followed an engineering apprenticeship and studied for an ONC and HNC in mechanical engineering at Nottingham colleges, then spent several years in further studies of ancillary engineering subjects.

At this early stage he worked in mechanical engineering, but moved into structural steelwork engineering where his interests were more readily satisfied. Subsequently, he joined a Civil and Structural Engineering consultancy practice in Derby where he acquired experience and knowledge of other construction materials, including concrete, aluminium, masonry, and timber. Additionally work frequently involved geotechnical engineering, a subject closely allied to his later interest in geology.

In preparation for the entrance examinations of The Institution of Structural Engineers, he became involved for several years in the part-time teaching of mathematics and engineering subjects at colleges in both Nottingham and Derby.

On being elected to membership of the Institution of Structural Engineers (M.I.Struct.E.) and becoming a Chartered Structural Engineer (C.Eng), he made a career move into local government in the Structures Section of Nottingham City Engineers Department. In 1973 he was appointed to the post of Principal Structural Engineer at Derby Borough Council, and later he moved to Chesterfield Borough Council as Group Structural Engineer in the Technical Services Department. Although a smaller Authority, work was much involved with geotechnical and geological matters, dealing with the problems left by a largely defunct coal mining industry. This concerned not only the provision of structural design and advice to client departments within the Council, but also with the letting and managing of contracts for the opencast mining of former colliery sites with subsequent redevelopment.

In 1994 he was involved in the refurbishment of Tapton House, which was leased by George Stephenson when he came to Chesterfield in the 1830s to construct the North Midland Railway, and was his home until his death in 1848.



In 1997 Brian took early retirement from local government. Not wishing to give up entirely, he has continued working part time in various Civil and Structural Engineering consultancy practices, and in the East Midlands Branch of The Institution of Structural Engineers.

From the mid 1970s, he attended adult education classes in Nottingham, developing his knowledge and interests, principally in geology, but also in a variety of other subjects such as natural history, vernacular architecture and, more recently, English literature and medieval history.

He was involved in the establishment of a WEA branch in Arnold, serving as Branch Chair for five years, before moving to the much larger Nottingham Branch and serving as Branch Chair for a similar period. It was as WEA representative on Centre Committee at the University of Nottingham's Adult Education Centre that his interest in adult education provision grew, and he occupied the post of Branch Treasurer for nine years, until Liberal Studies courses effectively ended at the University in 2008.

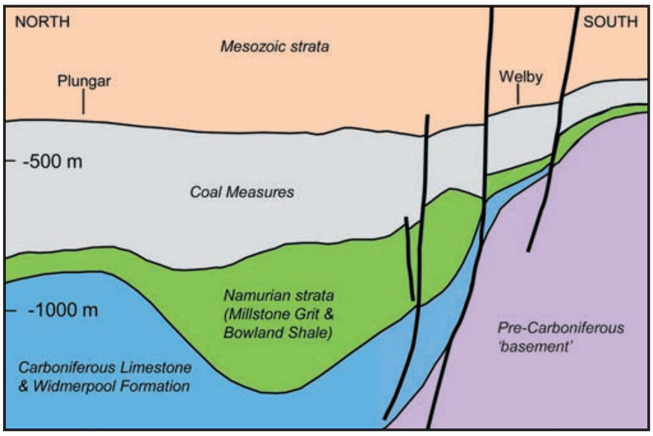
From the mid-1970s, he joined geology excursions both in Britain and abroad to the Western United States and Hawaii. These overseas trips were particularly inspiring and have been supplemented by holidays at home and abroad where investigation of the local geology has been a primary objective. Brian joined the EMGS soon after attending classes in around 1976, and ever since has been a frequent supporter at both indoor meetings and on field excursions.

GEOBROWSER

Energy from the Vale of Belvoir

The pleasantly rolling pastoral scenery of the Vale and its surrounding wolds are developed on Mesozoic strata that conceal one of the most important resources of fossil fuels in north-western Europe. Its value is emphasized by the prodigious amounts of money spent during the last century on exploration. Coal was first proved in the 1920's, during a programme of deep drilling by the D'Arcy Exploration Company (later to become BP). Following intensive exploration during 1973-76 the NCB (National Coal Board) announced reserves of 510 M tonnes, making this the largest unworked coalfield in Western Europe (Mann, 1980; Vale of Belvoir Inquiry Report: HMSO). Meanwhile a combination of geophysics, underground colliery data and seismic surveys had earlier located anticlinal structures suitable for oil or gas accumulation. Oil was first struck in June 1939 to the north of the Vale of Belvoir, at Eakring (QJGS, 1945, 255-317); during the Second World War, with the help of imported American expertise from Oklahoma, many more wells were brought into production and the search extended farther south, into the Vale. This resulted in 33 wells sited around Plungar, which produced 304,067 barrels of oil between 1953 and 1959, but today there are only two producing fields, at Rempstone and Long Clawson.

One major outcome is that the Vale of Belvoir now contains a wealth of subsurface information - well over one hundred exploration boreholes have been drilled for coal and oil, some almost a kilometre deep, and these are augmented by a network of seismic profiles which, with an aggregate length of over 1000 km, probably exceeds the combined length of roads and footpaths. A brief period of underground coal extraction from the Asfordby pilot colliery was fraught with geological problems and ceased in 1997 (Report, Mercian Geologist, 1998), but the search for new oil reserves continues and the stage is now set for a third exploration phase - for shale-gas, which was highlighted on the BBC's Sunday Politics for the East Midlands on the 24th March this year.



Simplified section across the Vale of Belvoir (after BGS).

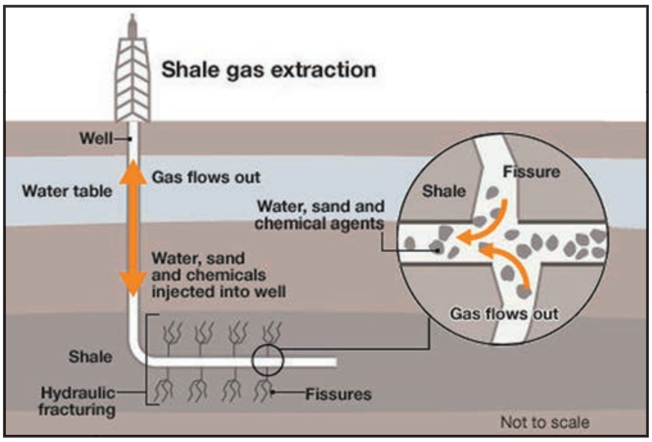
New prospects?

As we reported in Geobrowser for 2010, shale-gas could be a new hope for energy production and is a relatively 'green' resource of fossil fuel. Unfortunately however, sensational headliners have jumped on the bandwagon with titles such as: 'Rich Shale Gas Deposits found in Leicestershire' (http://thegwpf.org/uk-news/5321, from Leicester Mercury, 28 March 2012). On closer examination of this article we see that according to the BGS these are only potential 'deposits' that will require extensive sampling and drilling in order to prove. At the moment it seems that most prospection in the Vale of Belvoir will be directed at strata pre-dating the Coal Measures and in places lying at depths of over 1000 m. Due to syn-Carboniferous subsidence within a structure known as the Widmerpool Half-graben (or 'Gulf'), up to 500 m of potentially gas-rich source rocks are present in some parts. Of Namurian age, they are now referred to as the Bowland Shale Formation and are broadly equivalent to the unit formerly called the Edale Shale Group, which famously crops out at Mam Tor in Derbyshire. Rocks of similar age and lithology in the USA have proved suitable for gas production, causing a 'shale-gas revolution' there over the past 30 years; although the prospectivity of mudrocks is complex, and subject to a host of poorly-understood variables and the direct transfer of technologies to similar rocks in Britain is presently untested.

Fracking, earthquakes and toxic leakages

In order to extract shale-gas the enclosing strata must first be fractured, a process (hydrofracturing, or 'fracking') which involves pumping water and chemicals into shale rock at high pressure. Shale-gas exploration has attracted a vast amount of negative publicity associated with concerns including induced seismicity, demand for an already stressed water resource, and pollution of the local environment.

In Britain, the most alarming developments were the earthquakes of magnitudes 2.3 and 1.5 in April and May 2011 centred around the experimental fracking for shale-gas carried out by Cuadrilla Resources Ltd. at Preese Hall on the Fylde coast, Lancashire. An investigation confirmed that the timing of those earthquakes was closely related to that of fracking, and concluded that they most probably resulted from fluid injection that caused slippage along a pre-existing, critically-stressed



Method used for extracting gas from shale.

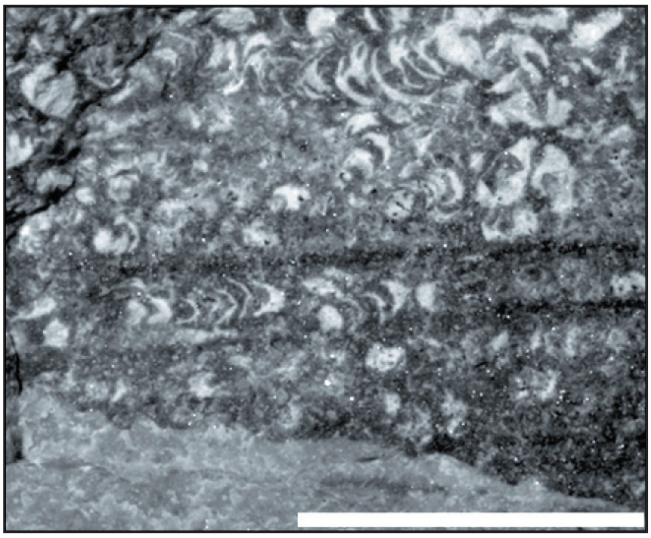
fault plane. The consensus of this and other reports, however, is that fracking-induced seismicity could be mitigated through a combination of close micro-seismic monitoring, more precise control over fluid injection, and the siting of injection intervals away from any fault systems identified in the borehole or known from geological surveys. Such occurrences should also be put into the local context, in that during the long history of underground coal extraction in Britain, mining-induced subsidence caused numerous events up to magnitude 3.

There have been several well-publicised reports in the USA of contamination of groundwater by methane, which in some cases has entered the domestic water supply via private water abstraction wells. The pathway in most cases is by poorly-completed gas abstraction wells, although it is worth stating that the regulatory regime in Britain is not the same as in the USA, and well integrity in Britain is covered by numerous stringent guidelines. Recommendations from the USA include assessing and continuously monitoring baseline data on groundwater quality and source of dissolved-gas concentrations before, during and after fracking (Proc. Nat. Academy of Science USA, 2011; 8172-8176). In Britain the BGS is currently undertaking the first part of this exercise, in order to establish baseline concentrations and likely sources of dissolved aquifer gases before any large-scale shale-gas exploitation begins.

If shale-gas extraction is proved to be commercially viable in the Vale of Belvoir, and the associated concerns can be satisfactorily controlled and mitigated without a prohibitive escalation of costs, then what are the chances of it going ahead? At the surface, the actual extraction sites for shale-gas are in themselves reasonably compact, but it is likely that a certain amount of infrastructure will be needed, such as booster stations and possibly a gas processing plant. The Environment Agency is currently supportive of shale-gas extraction but, as with all new power generation schemes in the UK, the final decision will most probably involve factors such as: national strategic necessity, local environmental 'pressure' and perhaps most importantly, a continued demand for safe, clean, indigenous sources of energy.

Precambrian bioturbation at Charnwood?

In 1995, a major upheaval in Charnian geology took place with the publication of a paper (Neues Jb. Palaeont. Abh. 195; 5-23) describing Teichichnus burrows in the Swithland Formation ('Swithland Slates'). Since Teichichnus is a deeply-penetrating burrow, and such features were unknown in strata of Precambrian age (i.e. pre-dating 542 Ma), the perceived wisdom was that the Swithland Formation was most probably Cambrian. This premise might now need to be revisited in the light of burrows described from of the Khatyspyt Formation (arctic Siberia), in a paper entitled: 'The oldest evidence of bioturbation on Earth' (Geology, 2012; 395-398). These burrows, named as Nenoxites, penetrate up to 5 cm in depth and represent both an intensely bioturbated ichnofabric as well as discrete, identifiable trace fossils. They occur in basinal mudstones and tuffs at a stratigraphical level constrained by U-Pb zircon determinations to be about 555 Ma old, which is 13 Ma before the end of the Precambrian. The appearance of Nenoxites is significant in two respects. First, it provides evidence that in the latest Precambrian there were animals capable of deep burrowing; and secondly it shows that for undated strata, such as the Swithland Formation, we may need to revisit certain of the palaeontological criteria previously used to assess their age.



Vertical cross section showing Nenoxites ichnofabric from the Khatyspyt Formation; the white scale bar is 1 cm long.

Australia’s metalliferous mineral wealth

Tim Colman

Abstract: Australia is a continent with substantial metalliferous mineral resources and a relatively small population. Large parts of the continent are underlain by ancient Archean and Proterozoic rocks. It has a rich mining history since Europeans first began settlement in 1788, and now derives about 41% of export earnings from minerals (when coal, oil and gas are included). There have been a number of mining ‘booms’; the early South Australia copper and Victorian gold rushes were largely self-financed, but the Western Australian gold rush of the 1890s and the iron ore boom of the 1960s, the nickel boom of the 1970s and gold boom of the 1980s involved substantial amounts of foreign capital. Currently there is strong Chinese interest in acquiring Australian mining operations and prospects. Australia now hosts four world-class mid-Proterozoic lead-zinc ore bodies, an early Proterozoic iron ore province with huge resources, the major Kalgoorlie camp of Archean gold, and the world’s largest resources of heavy mineral sands. Finally it has Olympic Dam, which is by far the world’s largest uranium deposit and also the fourth largest gold and copper deposit.

Australian geology is dominated by Archean and Proterozoic rocks together with extensive Phanerozoic basin cover (Fig. 1). There are two Archean cratons in Western Australia. The Pilbara craton is at least 3.2 Ga old while the larger Yilgarn craton is between 2.6 and 2.9 Ga old. The Gawler craton in South Australia is slightly younger and spans the Proterozoic/Archean boundary. The majority of the continent is underlain by Proterozoic rocks, locally with a cover of Paleozoic sediments. The eastern margin of the continent is bounded by Phanerozoic rocks, including a Palaeozoic volcanic arc, while the western margin has a narrow fault-bounded zone of mainly post-Palaeozoic sediments. The Australian continent has been geologically stable since the Cretaceous, apart from more recent volcanic episodes on its eastern fringe from Tasmania to Queensland.

As a result of decades of mineral exploration, Australia has become a major producer of iron ore, lead, zinc, copper, uranium, heavy mineral sands and coal (Table 1). Exports of metal ores in 2009-10 were worth A$45 billion, representing about 20% of the country’s total merchandise exports by value, and there were also large exports of coal, oil and gas.

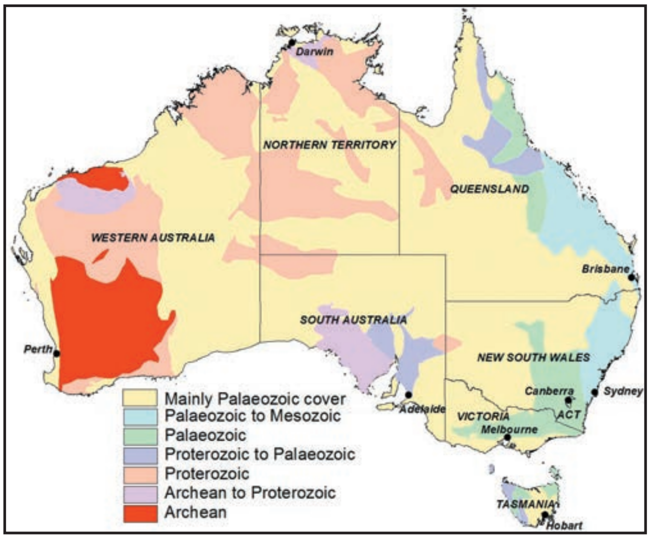


Figure 1*. Australian geology (after Geoscience Austalia).*

Early years to 1900

Australia underwent a long period of weathering and erosion as it slowly drifted north after separating from Gondwana at the end of the Mesozoic epoch. This caused development of a thick regolith including oxidised gossans over many sulphide-bearing ore deposits and the deposition of widespread alluvial gold in many areas. The native population did not make use of minerals or metals, so these deposits remained undisturbed until the arrival of European settlers. However, a number of ochre deposits were mined for use as body paint and some ochres were sometimes transported and traded over hundreds of kilometers. The largest was probably at Wilga Mia near Meekatharra in central Western Australia (Wilson, 1969) where an estimated 50,000 tons of material was removed in a series of open pits and small galleries. Following the first European settlement at Botany Bay in 1788, local Triassic Hawkesbury Sandstone was

	Australia production tonnes	World production tonnes	Australia % of world	Rank
Bauxite	65,843,000	199,000,000	33.1	1
Copper	854,000	15,800,000	5.4	5
Diamond	*10.8 M ct*	*121.3 M ct*	8.9	6
Gold	242	2,460	9.8	3
Iron ore	394 M	2,248 M	17.5	2
Lead	566,000	3,900,000	14.5	2
Lithium	4,400	18,000	24.4	1
Silver	1,633	22,236	7.3	4
Tin	13,269	279,000	4.8	5
Titanium	1,900,000	10,300,000	18.4	2
Uranium	7,942	50,700	15.7	3
Zinc	1,290,000	11,400,000	11.3	3
Zirconium	474,000	1,320,000	35.9	1

Table 1*. Australia’s world ranking in mineral production 2009; there is little or no current production of chrome, vanadium, tungsten, kaolin, potash, molybdenum, rare earths or fluorspar, though significant resources of these are known (after British Geological Survey).*

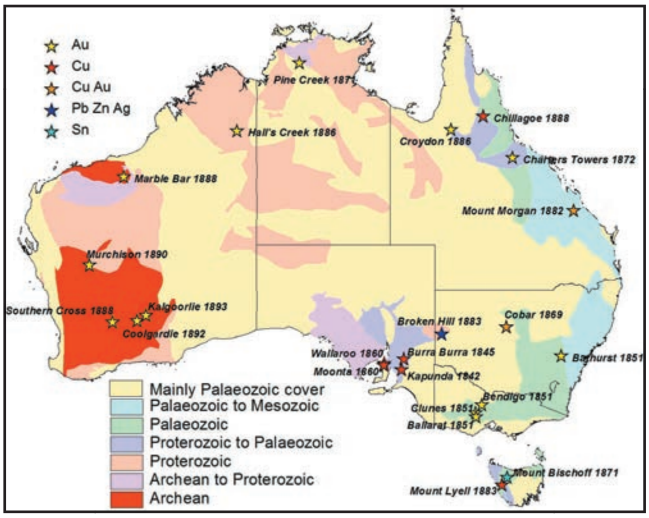


***Figure 2**. Significant mineral deposits discovered by 1900.*

quarried for building use and coal seams were found at outcrop at Newcastle, north of Sydney. However, there appeared to be little prospect of metalliferous minerals in the narrow strip of land between Sydney and the 'impassable' Blue Mountains. There were tales of sporadic discoveries of gold and other minerals by shepherds and escaped convicts from the penal colonies of New South Wales and Tasmania, but these were not followed up.

The first mine (other than the early coal mines near Sydney) to be developed by Europeans in Australia was the short-lived Wheal Gawler lead mine, discovered in 1841 by Cornish immigrants in Glen Osmond near Adelaide in the free colony of South Australia. More lead veins were found nearby and a small smelter was erected, but all the mines closed in 1851 when the miners rushed to the newly discovered Victorian gold field. In 1842 a bright green outcrop of malachite (copper carbonate) was found at Kapunda, north of Adelaide (Fig. 2). The success of this mine encouraged further prospecting and the Burra Burra deposit, also of malachite, was found in 1845 in late Proterozoic dolomite. This was much larger and was worked for the next 30 years, providing £800,000 in dividends for the local investors. South Australia produced 10% of world copper output in 1850 and was known as the Copper Kingdom. In 1860 copper was found at Wallaroo and Moonta on the Yorke Peninsula south of Adelaide in early and mid Proterozoic rhyolitic porphyry and metamorphic rocks of the Gawler craton. These deposits proved to be even larger, producing 350,000 t of copper from 7 Mt of ore over the next 60 years. The rise of South Australian copper mining in the 1850s and 60s coincided with the decline of tin mining in Cornwall (Fig. 3) and the mines were worked almost entirely by Cornish miners and mine captains, keeping the same terminology and traditions (Pryor, 1962).

***Figure 3**. Cornish-style engine house at Moonta mine, SA.*

Gold in eastern Australia

The California gold rush of 1849 caused many young Australians to try their luck in America. The New South Wales Government became worried about the lack of labour and offered rewards for the finding of 'payable gold'. In April 1851 gold was found by Hargraves, Lister and Tom at Ophir, near Bathurst, about 300 km west of Sydney beyond the Blue Mountains. Hargraves was awarded £15,000, but most was withheld after protests from his partners (Blainey, 1978). On 1st July 1851 the colony of Victoria broke away from New South Wales and later that month gold was found near Clunes northwest of Melbourne. Within a few months major deposits of alluvial gold had been found at many places nearby, including Bendigo and Ballarat and the Victorian gold boom began. As the native population had no interest in collecting gold, the product of many thousands of years of erosion had collected in streams and soils over the quartz veins or reefs in which it had formed. The population of Melbourne quadrupled in four years as the boom took hold. The authorities, unprepared for the change from a pastoral to a mining economy and having to cope with increased expenses of policing the gold fields, introduced the draconian Miner's Licence which cost £1 per month. This entitled the miner to work a piece of land of just 144 ft^2 (13.4 m^2), and had to be paid regardless of whether or not gold was found. Discontent with the aggressive policing of the licences led to the famous Eureka Stockade incident at Ballarat in 1854 where around 30 people were killed during a challenge to the government's authority. An enquiry led to most of the miners' grievances being settled with an annual Miner's Right costing £1 per year replacing the Licence and a reasonable mining claim system, with pegging of boundaries, that endured for the next century.

The Victorian gold fields were rapidly developed over an area of about 150 by 75 km. At first only alluvial and eluvial gold was recovered by panning and sluicing and then by shallow shafts to bedrock. This phase lasted for over 10 years with an annual production of over 2 M ounces of gold. The source of the gold was soon traced to outcrops of quartz veins or 'reefs' in the Lower Paleozoic slate and greywacke country rock. After initial shallow surface workings by

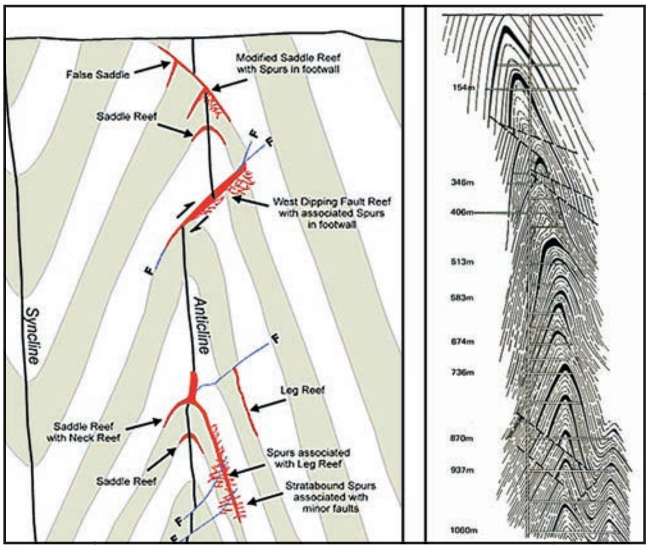


***Figure 4**. Schematic view of reef structures (left) and section of Great Extended Hustler's mine (right) showing saddle reefs in the goldfields of Victoria.*

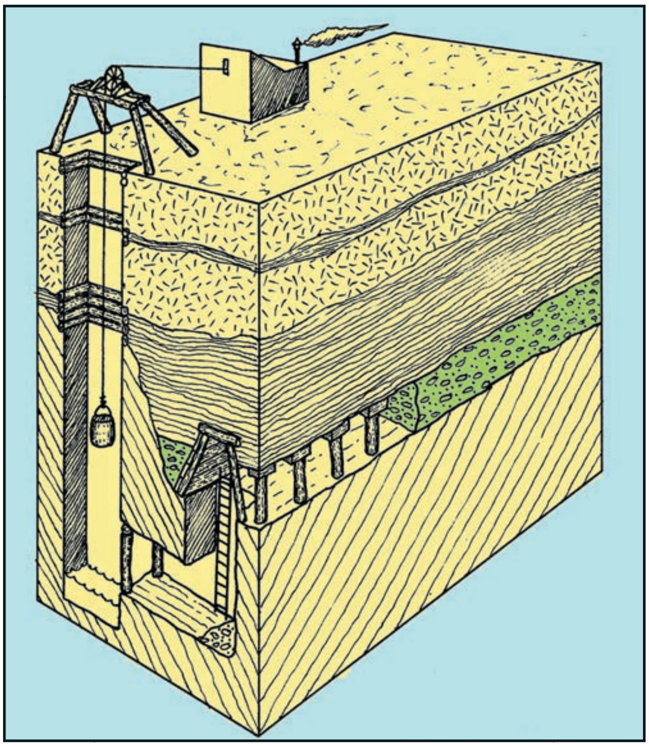


***Figure 5**. A deep level mine in the Victoria goldfields, with the payable deep lead in green (after Canavan, 1988).*

small groups of prospectors, companies were formed to raise the capital for underground mining. The most productive areas of the reefs were in 'saddles' draped around the crests of faulted anticlines (Fig. 4). Lines of these saddles were followed for several kilometers in the Bendigo area with more than 5000 shafts up to 1200 m deep (Willman and Wilkinson, 1992). Part of the area was covered with Tertiary basalt that infilled and covered preexisting valleys, which also contained alluvial gold. These 'deep leads' were worked by sinking shafts beneath the basalt at depths of over 150 m (Canavan, 1988), and required considerable pumping to enable working to continue (Fig. 5). The area is noted for the number of nuggets, with over 1300 exceeding 20 ounces including the Welcome Stranger containing 2394 oz (68 kg) of gold (Fig. 6). Gold production peaked at 89 tonnes in 1856 and then began a slow decline until the First World War when it dropped from 12 t in 1914 to 4 t in 1919 and never recovered. Total production from Victoria is about 74M oz (2100 t). The Victorian gold field is now considered to be a classic example of the Slate Belt or Orogenic class of deposits formed by metamorphic fluids depositing quartz and gold in low-pressure zones at the hinges of anticlines, faults and other structures during the later stages of folding. The process may be assisted by granitic intrusions forming structural features or increasing heat flow.

A rich tin deposit was discovered by 'Philosopher' Smith in 1871 at Mount Bischoff in western Tasmania after a decade of prospecting (Blainey, 1967). Over 60,000 t of tin metal have been recovered from the skarn and greisen mineralization associated with a Devonian quartz-feldspar porphyry dyke swarm from a nearby granite intruding late Precambrian sediments. The resulting rush to the new mining field provided the impetus for further prospecting that led to additional discoveries in the region.

In 1882 a syndicate including William Knox D'Arcy, opened a gold mine at Mount Morgan on the Queensland coast (Blainey, 1978). The gold was in a prominent ironstone outcrop which was the gossanous capping to what later proved to be a major copper-gold deposit of volcanogenic massive sulphide (VMS) type in Devonian acid volcanic rocks intruded by granite. The gold and the underlying copper deposit were very profitable and D'Arcy's one third share was worth £6 million within three years. D'Arcy used his profits from the mine to live a life of luxury in England with

IOCG: iron oxide copper gold class of ore deposits.
Sedex: sedimentary exhalative class of ore deposits.
VMS: volcanogenic massive sulphide type ore deposit.
BHP: Broken Hill Proprietary Company.
CRA: Conzinc RioTinto of Australia.
WMC: Western Mining Corporation.
WA, NT, SA, QLD, NSW: Australian states etc..

***Figure 6**. With its happy finders at Ballarat, the Welcome gold nugget was second in size only to the Welcome Stranger.*

London and country houses. He also funded the first oil exploration in Persia in 1901 with a huge concession of 1.2M km^2 for 60 years in return for £20 000, some shares and a 16% stake in any oil found (Blainey, 1978). The exploration absorbed so much money that he was forced to sell much of his interest in the concession to Burmah Oil. After nearly abandoning the search, a major oil discovery was made in 1908 and the Anglo-Persian Oil Company was formed and opened a large refinery at Abadan in 1913. The sulphurous oil proved difficult to sell until Winston Churchill persuaded the British Government to buy 51% of Anglo-Persian just before the start of the First World War to supply the British navy with oil. The company later became British Petroleum. Mount Morgan continued in production until 1981 with a total output of 387,000 t of copper and 262 t (92M oz) of gold to be Australia's fourth largest gold producer.

Broken Hill

The major and iconic Broken Hill lead-zinc-silver deposit was found in 1883 when Charles Rasp, a boundary rider, prospected an ironstone outcrop in the extreme west of New South Wales. He brought back samples of galena and cerrusite and a number of prospectors flocked to the new discovery (Blainey, 1978). Rasp and six associates pegged 120 ha covering the 3 km outcrop along the centre of the lode and formed the Broken Hill Proprietary Company (BHP). They soon found the galena was silver-rich and the oxidized top of the deposit contained native silver and other silver-bearing minerals. A silver boom ensued with many companies staking claims around the BHP block. Some were successful in working the very rich oxidized silver-rich capping. Beneath, lay a series of phenomenally high-grade lead and zinc orebodies. At first only the lead-rich portions were worked as, although the zinc-rich material was also high in lead, it was impossible to separate the two metals economically. Thus large dumps of millions of tonnes of zinc-rich tailings accumulated in the first decade of mining.

The Broken Hill ore bodies form one of the world's largest natural accumulations of base metals. An estimated 280 Mt of ore containing around 30% combined metal existed prior to mining, and the ore currently mined has grades ranging from 2.5—15% Pb, 20–300 g/t Ag and 5–20% Zn. The large size of the orebody, and particularly the fact that the original prospectors secured large portions of the lode and had the funds and the vision to employ the best engineers to develop it, led to Broken Hill being in the forefront of many developments in mineral processing, mining techniques and ore genesis. The directors of BHP went for managers, not to Cornwall – then the source of most mining expertise in Australia – but to the western USA, where the great Comstock Lode in Nevada and the many mines in Colorado were encouraging the rapid development of mining and processing techniques. William Patton was hired as general manager of BHP at the enormous salary of £4000 and Herman Schlapp from Colorado became chief metallurgist (Blainey, 1978). Square-set stoping from Comstock, using large timbers, became the preferred mining method in the wide and unstable stopes of the Broken Hill mines.

The large amounts of zinc-rich 'waste' (6.5 Mt at 19% Zn by 1904) prompted an urgent search for a solution. A number of schemes were tried by many companies before various methods of froth flotation succeeded in producing separate lead and zinc concentrates for smelting around 1905. Flotation was first patented by Elmore in 1898 at the Glasdir copper mine in North Wales, and was then developed separately and competitively by Delprat and by de Bavay and Potter, both brewing technologists. The process unlocked the full potential of the enormous orebody, and Broken Hill became a major world supplier of both lead and zinc. The development of the flotation process gave rise to a long and expensive litigation as the details of the various patents were compared (Mouat, 1996). No one actually knew exactly how flotation worked, least of all the numerous lawyers and judges who ruled on the merits of each method. Within a few years froth flotation was in use all over the world, having been developed in the intense competition around the Broken Hill field. It enabled the development of the large low-grade copper ores of the western USA and South America and was one of the century's outstanding advances in mineral processing.

The origin of the Broken Hill deposit has been investigated by many geologists. It occurs as a series of sub-parallel lenses over a width of 200 m and strike length of 14 km in highly metamorphosed mid-Proterozoic host rocks of gneiss and schist. Each lens has distinct proportions of lead and zinc. Numerous hypotheses have been advanced. It was not a quartz vein lode with which the early prospectors were familiar. There appeared to be no granite intrusion nearby giving rise to 'mineralising fluids'. An epigenetic replacement origin became the accepted theory with lens by lens replacement of the original rocks by successive pulses of 'mineralizing solutions' carrying lead and zinc. The metamorphism and complex structure were also advocated as important parts of the mineralizing process. However, some geologists were unsatisfied with these increasingly complex explanations. From the 1950s, Haddon King and then R L Stanton put forward the idea that the orebodies had been formed early in the depositional process, before deformation and metamorphism, and might even have been formed by hydrothermal solutions exhaling metal-rich fluids onto the sea floor with the metals being precipitated by reactions with hydrogen sulphide. This novel hypothesis attracted much criticism at the time but has gradually been accepted, with various modifications, as knowledge of basin dynamics and mineral chemistry has improved, and the 'Broken-Hill-type' ore deposit has become part of the Sedimentary Exhalative (Sedex) class of ore deposits.

Mount Lyell, Tasmania

In 1883 prospectors found another large ironstone gossan at Mount Lyell in the temperate rain forests on the west coast of Tasmania (Fig. 7). This had been missed by a protégée of Murchison, Charles Gould, who had led two Government-sponsored expeditions across the island twenty years before to look for gold and had even camped for a week a short distance from the gossan. Gould named the three largest local peaks Owen, Sedgwick and Jukes after strong opponents of Darwin whose *Origin of Species* was published just before Gould left England. The three smaller peaks were named after Darwin and his supporters, Lyell and Huxley (Blainey, 1967). The prospectors blasted, crushed and panned the gossan to recover small amounts of gold, but were convinced that it concealed a larger deposit, like that at Mount Morgan in Queensland. The company they formed struggled for a few years before collapsing in debt.

By chance, a group of Melbourne mining financiers came to Tasmania to invest in the then-bonanza Zeehan silver mines, on the back of the Broken Hill silver boom. They were led by Bowes Kelly who had bought a fourteenth share in the Broken Hill Proprietary mine for £200. Within six months it was worth £70,000 and within six6 years was worth £1,250,000 including dividends. The Melbourne group heard about Mount Lyell and sampled the mine. The samples were salted with gold but also contained significant percentages of copper. The original owners thought they were selling a failing gold mine; the purchasers hoped they were buying a large copper mine. The Melbourne group paid £5000 for a controlling interest in the mine and floated The Mount Lyell Mining Company with 100,000 £1 shares – within six years each share would be worth £6. However, the early years were difficult, with costly transport and labour and a difficult ore body. The discovery of a bonanza pod of 850 t of ore with silver at over 1000 oz/t and over 20% copper yielded a profit of over £100,000 and kept the company solvent until a rack-and-pinion railway using the Abt system had been built to connect with the port of Strahan 33 km away. Finally, in 1896, the newly appointed American metallurgist, Robert Sticht, proved that the pyritic copper ore could be smelted using pyrite as the main fuel, with coke only at start-up, and quartzite as a flux. The resulting sulphur dioxide fumes devastated the steep slopes of the surrounding mountains, but the process proved economical and profitable, even though the grade of the main orebody decreased with depth.

Figure 7. Mineral-rich Mount Lyell in Tasmania.

***Figure 8**. The worked-out Iron Blow open pit at Mount Lyell, Tasmania (photo: CMT).*

The Mount Lyell company engaged in intense competition with a rival on the field, the North Lyell Company. This had a much richer orebody but was managed from Britain. The North Lyell directors insisted on all materials, including bricks for smelters, being sourced from the home country, which caused unnecessary delay and expense. They also insisted on a separate railway to the sea. The Mount Lyell company was managed from Melbourne and the directors made frequent visits. The buildings were erected using local timber saving money and time. Within a few years the North Lyell company was bankrupt and taken over, in 1903, by Mount Lyell, which found that the North Lyell ore was rich in silica and therefore self-fluxing (Blainey, 1967).

Mount Lyell's ore has continued in almost continuous production until the present day. The original Iron Blow massive pyrite open-pit (Fig. 8) was replaced by the Prince Lyell open-pit working a semi-vertical stockwork of sulphide veins before underground operations on the Prince Lyell orebody commenced in the early 1970s. The group of varied deposits in the

The meaning of 'resources'

The term 'resources' has been used to include both ore reserves and resources (which have specific meanings and financial implications). They have been gathered form a wide variety of sources, including published company figures on company websites, scientific papers and journal articles. The text includes 'resources' from deposits that have been worked over a long time, some that have been worked out and others yet to commence production. The meanings of the terms reserves and resources have changed with time, so the values stated in the text should not be used for any purpose without thorough checking.

Mount Lyell area is now recognized as a classic set of VMS deposits in the Cambrian Mount Read Volcanics. They incorporate massive sulphide, stockwork, chert breccia and banded lead-zinc orebodies as well as a secondary ore deposit of native copper in Ordovician clays. The total mineral endowment of the Mount Lyell deposits has been calculated at 311 Mt at 0.97% Cu and 0.31 g/t Au (Seymour *et al.*, 2007). After many years as an independent company the Mount Lyell Mining and Railway Company was bought by Consolidated Gold Fields Australia in 1965 and is now owned by Sterlite Industries of India. Mining of 1.8 Mt ore in 2009/10 produced 23,160 t of copper. Current resources are estimated at 14.3 Mt at a grade of 1.3% Cu.

A lead-zinc deposit was discovered in 1894 by a prospector seeking gold at Rosebery in western Tasmania about 30 km north of Queenstown. The township was named after the British Prime Minister at the time. However, it was to be another 40 years before the fine-grained intimately intergrown galena and sphalerite minerals could be effectively and efficiently separated to produce the metals. This deposit is also hosted in the Mount Read Volcanics.

Gold at Kalgoorlie

In the 19th century Western Australia appeared to have relatively few mineral deposits, although only a small number of exploratory parties had traversed it due to the lack of water. Lead and copper veins were worked after 1850 in the Northampton area, near the coast north of Perth. The veins are hosted in shear zones in mid-Proterozoic gneiss associated with early sub-parallel dolerite dykes. Total production was about 77,000 t of lead and 2500 t of copper. Gold was found at Hall's Creek in the Kimberleys in 1884, and the ensuing rush brought many prospectors to the area. As they spread out, gold was found in the Pilbara two years later and then east of Geraldton in the Murchison and at Southern Cross east of Perth (Wilson, 1969). In September 1892 Bayley and Ford found the Coolgardie field; Bayley rode into Southern Cross to register his finder's reward claim with 554 ounces of gold (nearly 16 kg, worth around £600,000 today). The effect was sensational, and hundreds made their way to Coolgardie, including a small Irishman, Paddy Hannan (Casey and Mayman, 1968). Within a few years Coolgardie had an impressive stone-built Mining Warden's court, flourishing mines and a burial ground that was filling rapidly due to numerous outbreaks of typhoid. In June 1893, Paddy Hannan and his companions found alluvial gold where Kalgoorlie now stands (Fig. 9). Prospectors rapidly realized that gold was found almost exclusively in the relatively narrow 'greenstone belts' and not in the more extensive areas of granite. It is now recognized, following the systematic remapping of the Yilgarn shield by the Geological Survey of Western Australia in and after the 1960s, that the greenstone belts occur as sequences of ultrabasic lavas, basaltic lavas, rhyolites and clastic sedimentary rocks. There are also numerous acid, basic and ultrabasic intrusive rocks. The ultrabasic lavas are komatiites and commonly exhibit 'spinifex texture' with long crystals of olivine. This has been interpreted as a quench texture of a very hot fluid, and appears to be restricted to Archean komatiites (Fig. 10).


Figure 9*. The statue of Paddy Hannan in Kalgoorlie (photo: D Graham).*

The new Coolgardie-Kalgoorlie gold rush coincided with an Australian financial crisis that caused bank failures and company insolvencies. However, English capital was looking for an investment at this time and gold and other mining shares promised exciting returns. English money flooded into Australia, with 94 WA gold mines floated in London in 1894 (Fig. 10). There were of course some scams and scandals. A quartz vein at Londonderry near Coolgardie yielded 10,000 ounces in 1894 from a hole 1.5 m long and 1.2 m deep (worth around £10M today) including a 100 kg lump containing nearly 40% gold! The lease containing the hole was bought for £180,000 by the Earl of Fingall who was seeking investments for an English syndicate. The hole was sealed and Fingall returned to Britain to raise 700,000 £1 shares in the Londonderry Gold Mining Company to develop the 'mine', of which only £50,000 was for working capital, the rest went on promoters'

Figure 10*. Spinifex texture in komatite at Ruth Well, Pilbara.*

and vendors' shares. An output of five tonnes of gold in eight weeks was predicted. The hole was duly re-opened and found to contain almost no more gold.

Fortunately, the area survived the bad publicity. With few exceptions, the rich surface shows at Coolgardie failed to continue at depth. However, those at Kalgoorlie were the opposite, with little surface gold but with rich ore shoots continuing to depths of over 600 m in the Archean amphibolites and serpentinite host rock. Within ten years a pipeline using a revolutionary locking-bar system had been constructed to bring water over 550 km from Perth to Kalgoorlie; until then water had to be condensed from salt lakes using local timber as fuel (Casey and Mayman, 1968). The price of water dropped by around 90% as a result of the pipeline. Gold production in Western Australia rapidly climbed from 3 tonnes in 1893 to reach a maximum of 64 tonnes in 1903. The Golden Mile has continued in production to the present day with 50M oz (over 1400 tonnes) of gold extracted by 2003.

From 1900 to 1960

The first half of the 20th century saw continued development of some existing mining areas, the decline of many of them and the slow emergence of the major Mount Isa deposit (Fig. 11).

The original BHP mine leases, at the crest of the boomerang-shaped orebody, were approaching exhaustion by 1915 and the directors decided to diversify into steel making. This required coking coal, which they worked in mines near Newcastle. So BHP, the biggest industrial enterprise in Australia, grew up based on iron ore from the Proterozoic banded iron deposits of South Australia and the coal of the Hunter Valley, northwest of Sydney (Blainey, 1978). The other Broken Hill companies, Broken Hill North, BH South and the Zinc Corporation all continued to develop their orebodies at increasing depths along both ends of the 'boomerang'. The last remaining workings on the Broken Hill field are Perilya's Southern Operations and CBH Resources' Rasp Mine in the centre of the lode. Perilya are mining about 1.5 Mt of ore per year with reserves of 14.7 Mt at 5.3% Zn, 4% Pb and 42 g/t Ag and resources of 12.7 Mt at 8.9% Zn and 6.8% Pb and 67 g/t Ag. The Rasp Mine is intended to extract the high-grade pillars left unmined from the old Main Lode orebody and also the unmined Western Mineralisation. The total resources were stated by CBH Resources in 2009 as 16.5 Mt at 6.6% Zn 5.1% Pb and 89 g/t Ag. It was bought in 2010 by Toho Zinc of Japan. Production is expected to commence in 2012.

An amalgamation of several Broken Hill mines formed the Electrolytic Zinc Company during WW1 to produce zinc domestically when they were cut off from Germany, which had previously taken their zinc concentrates for smelting. They built their reduction works at Risdon, near Hobart in Tasmania, to take advantage of cheap hydroelectricity, with the first zinc being produced in 1918. They then went on to acquire the Rosebery deposit from Mount Lyell, which realized that it could not raise the funds to build its own zinc works in western Tasmania. However, Mount Lyell had done the pilot-plant work to enable the complex Rosebery ore to be separated economically. Rosebery began full-scale production in 1936 and has continued to the present day with current production at 700,000 t/yr of high grade ore (12% Zn, 4% Pb, 0.3% Cu, 1.7 g/t Au and 125g/t Ag). It is now owned by Minmetals Resources Ltd of China and has current reserves and resources of 16.9 Mt at 11.8% Zn, 4.0% Pb, 0.4% Cu, 136g/t Ag and 1.8g/t Au.

Exploration during the 1930s in the Captain's Flat area, near Canberra, previously worked largely for gold from 1882 to 1899, proved a substantial deposit of copper, lead and zinc. Connection to the rail network in 1937 enabled Lake George Mines to open a mine which operated until final closure in 1962. Total production was over 4 Mt of ore with an average grade of 10% Zn, 6% Pb, 0.67% Cu and 1.8 oz/ton Ag (Glasson and Paine, 1965). The lens-like orebodies occur in strongly folded Lower Palaeozoic volcano-sedimentary rocks and are now thought to be of volcanic exhalative origin. The area is now being investigated by various companies.

The Western Australian goldfields expanded and developed in the early 20th century, but only a few small deposits were discovered after WWI. The larger mines such as Sons of Gwalia at Leonora (managed by Herbert Hoover for a time) and Big Bell near Cue continued until the early 1960s (Fig. 12). By then only Kalgoorlie and Norseman were still producing, as the gold price had been pegged at $35 per ounce since 1934. A number of mines on Kalgoorlie's 'Golden Mile' were working over 300 separate ore bodies on many levels down to almost 1000 m deep by 1960. The gold is hosted in faults, shear zones or quartz vein systems in Archean greenstone belts, with some in pyrrhotite bodies within banded iron formations, such as at Mount Magnet. The 1930s saw an upsurge in prospecting due to the Great Depression and the state government's

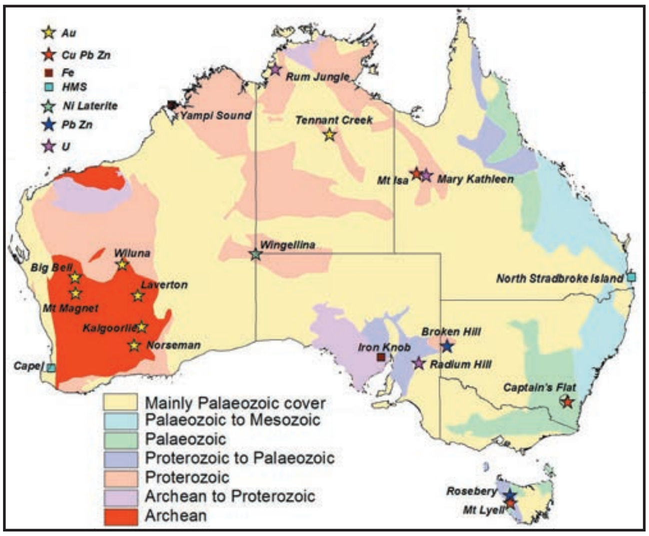


Figure 11. *Significant mineral discoveries from 1900 to 1960.*

***Figure 12**. Shaft headgear at the Sons of Gwalia gold mine.*

assistance by providing tools and continuing the State Batteries (small crushing and processing plants) that treated small mines' gold ore at a subsidised charge. The Australian Government also introduced a 'Gold Bounty Bill' of £1 per ounce in 1930 to maintain employment in the goldfields and assist national balance of payment problems. The outback legend of Lasseter's Reef was revived and in 1930 an expedition led by Lasseter attempted to rediscover the fabulous gold-rich quartz reef he claimed to have found when travelling from Alice Springs to the WA gold fields in 1897. The expedition ended in acrimony and disaster, with Lasseter dying alone in the bush (Blainey, 1978). The 1930s also saw the start of the Kalgoorlie-based company Western Mining Corporation (WMC) which was unusual in being headed by mining engineers and geologists and in always spending a significant amount on exploration. This far-sighted policy was to pay dividends in the coming decades. An early success for WMC was the development from 1936 of the Crown, Maraora and Princess Royal gold mines at Norseman, which have now produced over 5 M ounces of gold (over 140 tonnes). Victorian gold production declined sharply in the early 20th century, and had almost disappeared by the early 1920s.

There was a minor rush to mine alluvial osmiridium (a natural alloy of osmium and iridium) in serpentinite near Adamsfield in Tasmania 50 km west of Hobart in 1925 (Bacon, 1992). Osmiridium had been known in northwest Tasmania for some years; in fact the only recorded (up to that time, in 1913) *in situ* occurrence in the world in rock was in serpentinite near Waratah, and an Osmiridium Act had been passed in the Tasmanian Assembly in 1919 to regularize the small industry. The rush to Adamsfield by up to 1000 miners led to a ten-fold increase in output to over 3000 ounces when the price was over £30 per ounce. Interestingly there was a penalty for including osmiridium in panned gold as the two were difficult to separate except by dissolving the gold in mercury. The rush only lasted a few years before the price dropped to less than £10 per ounce.

Mount Isa

The great Mount Isa lead-zinc-copper-silver mine in northwest Queensland took many years to develop fully (Fig. 13). It was discovered by a prospector in 1923 and had a long gestation because of its isolation (Blainey, 1960). Over 11,000 m of surface drilling was completed between 1927 and 1931, which was then an astounding amount for a deposit yet to go into production. A number of companies controlled it, but it was not until the American Smelting and Refinery Company (Asarco) bought it in 1930 and installed Julius Krushnitt as general manager that output began. The deposit is another Sedex deposit comprising a series of sub-parallel steeply dipping lenses of lead and zinc sulphide in mid-Proterozoic metasediments adjacent to the major Mount Isa N-S fault and is similar to the Broken Hill deposit but of lower metamorphic grade. Just before WWII, a major, separate copper deposit was discovered at depth, adjacent to the lead-zinc lenses, in an unusual silica-dolomite host rock. The silica-dolomite hosted copper probably formed later than the lead-zinc with mineralising solutions using the same Mount Isa Fault as a focus and a conduit. This was a major source of copper during the war, when. Mount Isa, like Broken Hill, was a company town completely reliant on mining. By 1960 the mine was a major producer of lead, zinc, copper and silver. In 1947 exploration along the Mt Isa fault discovered the similar Hilton deposit 24 km north of Mt Isa. However, this did not go into production until 1990 when the George Fisher mine was opened. Reserves and resources of the Hilton deposit totaled around 58 Mt at about 8% Zn, 5% Pb and 100 g/t Ag in 2005.

Small high-grade deposits of gold, and later copper, were found from 1932 around Tennant Creek in the Northern Territory, 600 km west of Mount Isa. In 1949 a shaft sunk by Australian Development found gold in ironstone with grades of 50–60 oz/ton (about 1500 g/t). By 1960 the Nobles Nob mine had produced £8.5 million worth of gold and paid £4.5 million in dividends (Blainey, 1978). It continued production until 1985 for a total of a million ounces from 2 Mt of ore. Another company, Geo Peko, later used geophysics to locate high-grade copper-gold orebodies in pipe-like lenses of

***Figure 13**. Mine buildings above an old open pit at Mount Isa.*

magnetite along shear zones at depth in the host Lower Proterozoic sediments. A number of small to medium size mines (up to 15 Mt) such as Warrego, Peko and Juno were developed in the 1960s and 70s. Warrego produced 1.3M oz of gold and 91,500 t of copper, but the field is now inactive.

In 1955 Carpentaria Exploration, the exploration arm of Mount Isa Mines, found a major lead-zinc deposit of similar style to Mount Isa on the McArthur River in the Northern Territory. At first named HYC (Here's Your Chance) it took 40 years before the first ore was produced from this enormous orebody containing over 200 Mt at a grade of 10% Zn and 4% Pb in mid-Proterozoic unmetamorphosed sediments of similar age to those hosting the Mount Isa deposit 500 km to the south (Murray, 1975). For many years, the very fine grained and intimately intergrown sulphides of lead and zinc proved impossible to separate economically, and the deposit lay in limbo after the sinking of an exploration shaft in the early 1960s. The McArthur River deposit, like the Mount Isa lead-zinc deposit, is now considered to be important members of the Sedex class of mineral deposits, as described at Broken Hill. Iron ore was mined in South Australia by BHP from a series of Lower Proterozoic banded iron formation deposits in the Middleback Ranges such as Iron Baron, Iron Duke and Iron Knob and also from Koolan Island off northwestern Western Australia (Fig. 14). In 1938 an iron ore export ban was imposed, partly to curb growing Japanese influence and partly to conserve the apparently diminishing resources. About 100 Mt of iron ore was mined to the end of 1963 (Canavan, 1965), mainly by BHP for domestic consumption. This impressive figure was to be dwarfed in the coming decades. Exploration in the 1950s by BHP discovered significant Proterozoic oolitic iron ore deposits at Roper Bar and Constance Range in northern Queensland with several hundred million tonnes of resources. However, the iron ore export ban remained in place until 1962 when the growing discoveries in the Pilbara made it redundant.

***Figure 14**. Banded iron formation in the Pilbara, though this outcrop is of sub-economic material.*

The 1950s saw a national surge in uranium prospecting using the newly developed Geiger counter. Booklets were distributed to prospectors describing the characteristics of uranium minerals and how to look for them. Numerous cash rewards of up to £25,000 were collected for the discovery of several deposits such as Mary Kathleen near Mount Isa and Rum Jungle in the Northern Territory. These, together with Radium Hill in South Australia which had been found in 1906 and worked sporadically for radium in the 1910s and 1920s, were worked to produce uranium for Britain's nuclear weapons programme and then for power generation.

Mining of coastal sand dunes for heavy mineral sands containing rutile (TiO_2) and zircon ($ZrSiO_4$) began on the east coast in 1945 on North Stradbroke Island south of Brisbane. Similar deposits rich in ilmenite ($FeTiO_3$) were discovered around Capel and Bunbury, south of Perth, in 1955 (Baxter, 1990). By the late 1960s Australia was a major exporter of rutile and ilmenite for paint manufacture.

Bauxite

In 1955 geologists from Consolidated Zinc were looking for with prospects for oil and saw the red-brown cliffs around Weipa mission in northern Queensland on the coast of the Cape York Peninsula. Sampling showed it to be high-grade pisolitic bauxite at around 50% Al_2O_3 and production from this remote location began in 1961 by Comalco (Commonwealth Aluminium Corporation) from an original resource exceeding 3000M t. The Weipa deposit is now a major producer at a rate of over 16 Mt/y. A similar deposit was also found in 1955 at Gove in Arnhem Land in the Northern Territory, and was developed by Nabalco (North Australian Bauxite and Alumina Company), a joint venture between Alusuisse and CSR (Colonial Sugar Refiners). It is now a major producer of bauxite and alumina in spite of its remote location. Now, both are owned by Rio Tinto, and Australia produces a third of the world's bauxite (Table 1).

In 1957 Western Mining Corporation discovered large resources of bauxite in the Darling Range south-east of Perth in Western Australia. A mining lease of over 12,000 km^2 was granted and, although it is only 27-30% Al_2O_3 (one of the lowest grades worked economically anywhere), production in a joint venture with Alcoa started at the Jarrahdale deposit in 1963. The bauxite had previously been regarded as uneconomic as it was high in silica and relatively low in alumina. However, a WMC geologist, Roy Woodall, realized that the silica was due to quartz (non-reactive with the caustic soda used in treatment), not clay as in many bauxites, and could be easily removed, thereby upgrading the bauxite. Several mines are now active, including Alcoa's Huntly mine, which is the world's largest bauxite mine at 23 Mt/yr, and Worsley's (majority owned by BHP Billiton) Boddington mine at 12 Mt/y. Alcoa's WA refineries now satisfy 13% of world alumina demand.

From 1960 to 1975

This was a period of major discoveries and developments in iron ore, nickel, uranium and mineral sands (Fig. 15), and a huge increase in mineral exports to the rapidly developing economies of Japan and South Korea. It was also marked by the quiet decline of the gold mining industry as the price was still pegged at $35/oz. By 1975 only the Mount Charlotte low-grade, large-scale, underground mine was in operation, mining quartz stockwork mineralization at Kalgoorlie.

Iron ore in the Pilbara

The decade began with the discovery of immense deposits of high grade massive hematite in the Pilbara region of north-western Western Australia (Fig. 16). Although the presence of iron ore had been known for many years, no serious work had been done because the area was so remote and over 150 km from the coast where there were only small ports. Realizing that the export embargo was about to be lifted, the WA state government called for tenders in 1961 for mining companies to apply for exploration rights (Temporary Reserves or TRs) to large areas of prospective ground. A consortium of Consolidated Gold Fields Australia and the American companies Cyprus Mines and Utah Construction was granted several TRs in the Port Hedland region covering areas of Archean volcanic and sedimentary rocks. The consortium concentrated on the Mount Goldsworthy area where some drilling had already been carried out by the Geological Survey. Within four years 4M t/y of iron ore was being railed 200 km to Port Hedland for export to the booming Japanese and South Korean blast furnaces and steel mills, and the WA iron ore boom had begun (Fig. 17).

This was just a foretaste to the development of the enormous deposits in the 2500 Ma old late Archean-early Proterozoic rocks of the 2500 m thick Hamersley Group rocks in the Hamersley Range, several hundred kilometers south of Port Hedland.

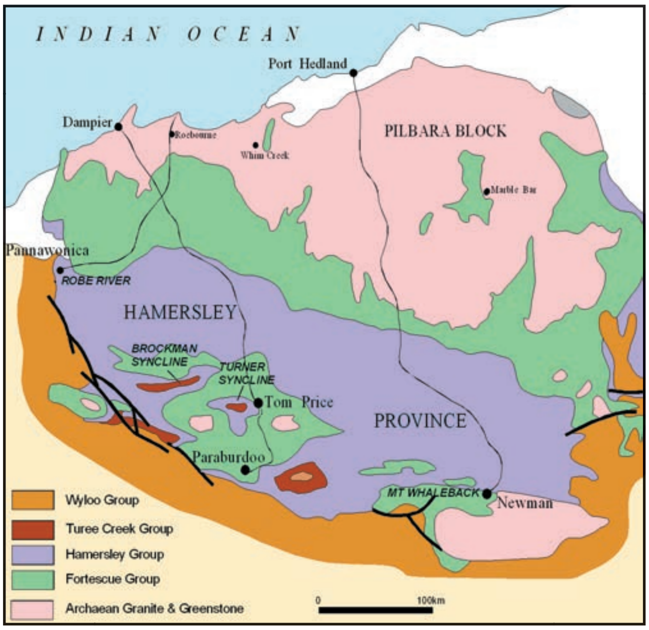


***Figure 16**. Outline geology of the Hamersley Range (after Data Metallogenica).*

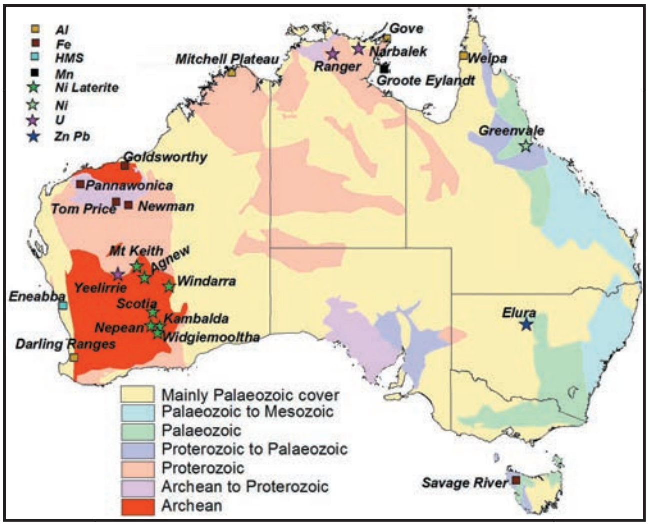


***Figure 15**. Significant mineral discoveries from 1960 to 1975.*

In 1952, Lang Hancock, a wealthy grazier with a large cattle station in the area, noticed extensive iron ore indications when flying over the area. Ground inspection revealed numerous outcrops of massive hematite. However, due to the export embargo it was impossible to peg any claims. Hancock pressed for the abolition of the embargo, but was unable to reveal his discoveries until it was lifted. He then pegged a number of areas in 1961 and sold the mining rights to Rio Tinto and Kaiser Steel. Production from the Mount Tom Price deposit began in 1966 based on an initial ore reserve of 900 Mt at a grade of 64% Fe (Fig. 18). The ore is railed 300 km to the coast at Dampier. A similar deposit was discovered by Stan Hilditch in 1957 at Mount Whaleback 200 km east of Tom Price while prospecting for manganese (Fig. 20). He too could not peg the deposit and had to wait until the embargo was lifted. Exploration by AMAX with partners BHP and CSR proved an initial resource of 1700 Mt also at 64% Fe. Production by the Mount Newman Iron Ore Company began in 1969 with ore railed 400 km north to the coast at Port Hedland.

Both these deposits occur in the Dales Gorge Member of the Brockman Iron Formation, a 600 m thick unit of banded iron formations (BIFs), shales and sandstones. The first economic orebodies were found where the BIFs, which are alternating laminations of chert and

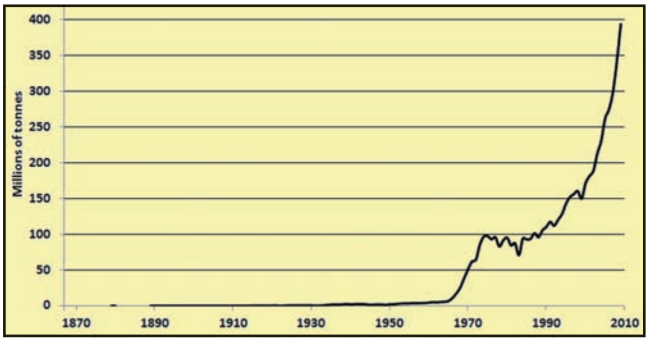


***Figure 17**. Iron ore production in Australia (after Mudd, 2009).*

***Figure 18**. The large open pits extracting iron ore at Mount Tom Price (photo: RTIO).*

hematite containing about 35% Fe, have been enriched by groundwater movement to form deposits of massive hematite. The base of the Brockman Iron Formation is marked by a distinctive resistant layer, named Bruno's Band after the geologist Bruno Campana who worked for Rio Tinto (Fig. 19). This feature enabled the discontinuous outcrops of the Brockman Formation to be mapped rapidly from the air. Dr Campana states that within a year hundreds of hematitic orebodies had been located aggregating 4 billion tons of iron ore ranging from 58% to 64% Fe. In 1969 Dr Edward Teller was consulted by Hancock Prospecting on the feasibility of using nuclear explosives to mine ore or to construct harbours more efficiently than conventional explosives. Fortunately this initiative came to nothing.

The early exploration in the Hamersley Province concentrated on the Brockman Iron Formation as it formed prominent outcrops. However, the underlying Marra Mamba Formation, which did not crop out so obviously, was also found to contain substantial mineralisation. This is now mined by BHP Billiton from an area west of Newman called Mining Area C. The Brockman section of this area was investigated by the Goldsworthy consortium in the late 1960s and early 1970s, but the Marra Mamba unit was then ignored as it was in a low lying flood plain with few outcrops.

Another significant iron ore deposit at Savage River in north-western Tasmania began operations in 1966 from a series of massive magnetite-pyrite lenses in late Precambrian schists and amphibolites. Concentrated magnetite slurry was pumped 85 km north along a pipeline to a pellet plant at Port Latta at the rate of 2.5 Mt/yr at a grade of 65% Fe for export to Japan.

A major bauxite area was found by AMAX in 1965 at Cape Bougainville and the Mitchell Plateau in the Kimberleys of Western Australia and resources of 1200 Mt of high-grade bauxite identified. However the deposits, now mainly owned by Rio Tinto Alcan, remain undeveloped due to the lack of infrastructure in this region.

In 1962 BHP examined a known occurrence of manganese on the remote Groote Eylandt in the Gulf of Carpentaria in the Northern Territory. It was soon apparent that this was of major significance and production began in 1966. The deposit is of sedimentary origin and occurs in Lower Cretaceous marine sands, clays and gravels overlying Middle Proterozoic sandstones with a lateritic capping (Bolton *et al*., 1990). The ore horizon is around 3 m thick and is worked in open cut mines by GEMCO (Groote Eylandt Mining Company); a joint venture between BHP Billiton and Anglo American. The total pre-mining resource was about 200 Mt at grades exceeding 40% manganese. Current production of over 4 Mt/yr is over 15% of world high-grade output.

***Figure 19**. Drilling for iron ore in Marra Mamba formation at Bungaroo, in the Hamersley Range, with crags along the Bruno's Band across the distant hillside (photo: RTIO).*

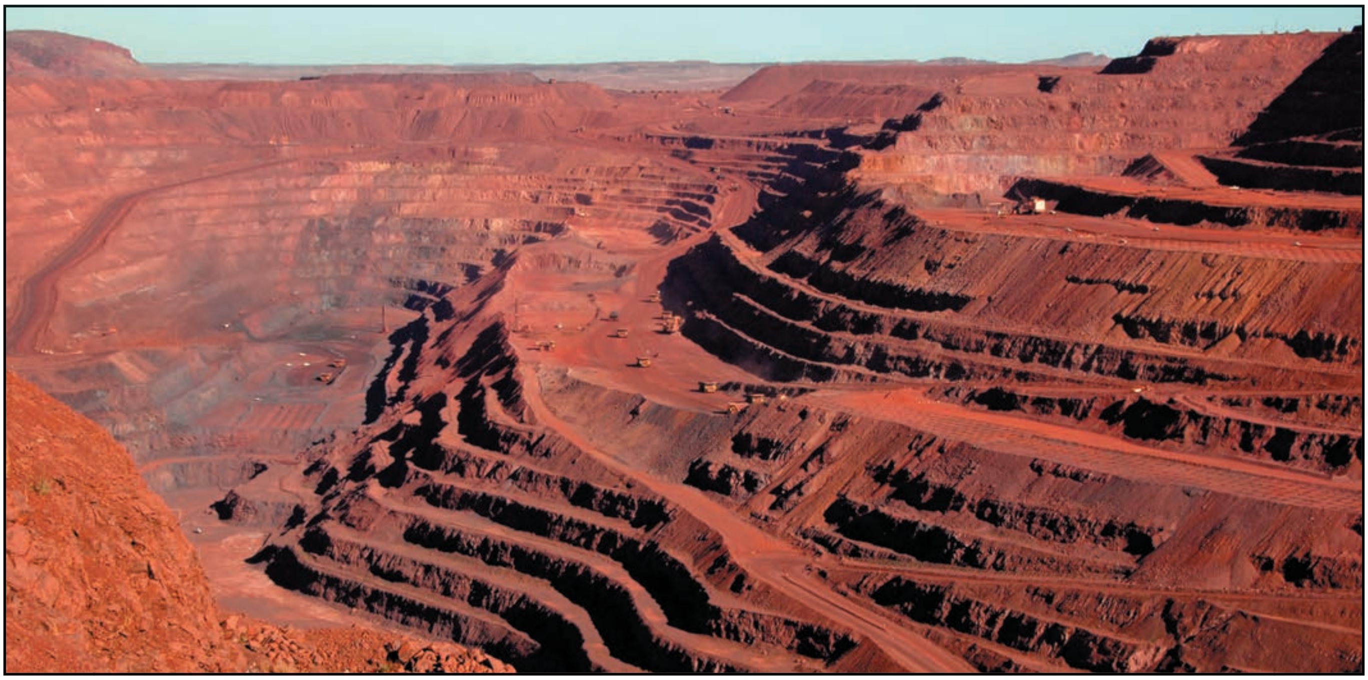


Figure 20. *Whaleback Mountain iron ore mine in the Pilbara.*

The nickel boom

In January 1966 Western Mining Corporation, a small Western Australian gold mining company, intersected 2.7 m of massive sulphides containing 8.3% nickel in an exploration drillhole at Kambalda, south of Kalgoorlie. Its announcement in April 1966 caused a stock market sensation as there was a world shortage of nickel due to a long strike in the Canadian mines and the price had soared. Western Mining had been exploring for some years looking for base metals south of Kalgoorlie along a 'greenstone belt' of Archean basic and ultrabasic lavas surrounded by granite on the premise that the area might be an analogue of similar rocks in the Abitibi belt of the Canadian Shield which host gold and also base metal deposits, including nickel.

John Morgan and George Cowcill had been prospecting in the area since 1939, and in September 1964 brought some samples of a bright green gossanous rock to Western Mining (Fig. 21). They had found them years earlier but they did not contain gold or copper. In the mid 1950s they had taken them to the School of Mines in Kalgoorlie, thinking they might contain uranium, but were told they had traces of nickel. In 1964, knowing that Western Mining were in the area, they took the samples to Roy Woodall, a senior WMC geologist (Woodall and Travis, 1969). He took out a Temporary Reserve over the Kambalda area and started exploration as, based on geological surface mapping, he suspected that there might be nickel sulphide deposits beneath the gossanous outcrops that were traced around a domal outcrop of ultrabasic extrusive rocks in contact with basalts and sedimentary rocks. Six holes were drilled with only the first hole intersecting mineralization. Fortunately the drilling of this first hole was continued beyond its target of the contact between the ultramafic extrusive rock and basalt, and intersected high-grade nickel mineralization that had been structurally displaced into the underlying basalt. No nickel was then known in WA, apart from some lateritic nickel discovered by INCO in 1954 in the Wingellina area of the Giles complex near the SA/NT border. A remote prospect then of no economic interest. Wingellina has since proved to have substantial resources.

The WMC nickel strike took the Australian stock market by storm. As more results were announced, WMC shares rose sharply reaching $76 before further share issues diluted the stock and brought prices down. Sinking the Silver Lake shaft into the Lunnon orebody, the first of many mines in the Kambalda district, started in July 1966, just 6 months after the discovery hole, and production began in April 1967 (King, 1973). Kambalda was developed as a company town to serve the needs of WMC's growing number of mines around the Kambalda dome, but Kalgoorlie boomed with over 200 mineral exploration companies based there by the late 1960s, together with supporting geophysical,

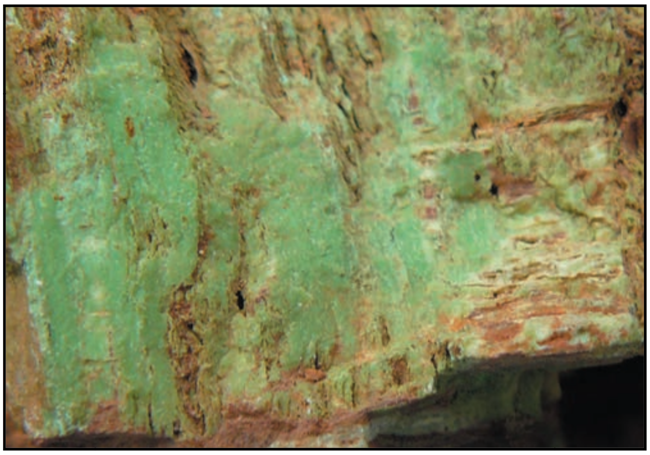


Figure 21. *Nickel gossan, mainly of garnierite, from the Kambalda region.*

analytical and drilling companies. All the world's major mining companies were there, plus a legion of small to medium sized local companies. The boom was fed by major industrial unrest at the then leading nickel producers at Sudbury in Canada. The spot price of nickel rose sharply from under $2000 per tonne at the end of 1968 to over $7000 by the end of 1969.

The pages of the Kalgoorlie Miner newspaper were full of lists of mineral claims and of company prospectuses, some of very dubious quality. By the end of the decade all a company needed to float on the stock exchange was to have about 100 rectangular 'claims' each of 300 acres with some nickel analyses in the hundreds or thousands of ppm and some 'ultrabasic rocks' (undefined) on at least some of the claims. The prospectors who pegged the claims were paid in shares in the soon-to-be-floated company, 200,000 or so shares were issued at a face value of 20 cents and promptly opened at 50c to $1 or so. Everyone was happy. Judicious announcements kept the share price volatile until the next company issue came along. One prospectus map purported to show the outlines of 'the ultrabasic'. What it actually showed, in a fairly remote area 100 km northeast of Kalgoorlie, was the outlines of a dry salt lake copied from an old Geological Survey map! Another group of claims of very dubious ancestry had samples assaying 5% nickel, which was astoundingly high. Unfortunately the samples were nickeliferous laterites swept into the creek-bed claims from higher, more promising WMC ground – the only alluvial nickel deposit ever reported! The worthless claims were later sold for $1 million to a minor exploration company. In 1972 a small exploration company, Leopold Minerals, announced an intersection of 7.5 m at 3.3% Ni in a new area near Nullagine in the Pilbara (Sykes, 1978). The assays appeared suspiciously like those from the WMC Kambalda camp; this were confirmed when the promoter was arrested at Perth airport trying to leave for Singapore, and a parallel hole, drilled under police supervision, failed to show any sign of mineralisation. The original material probably came from a WMC core store adjacent to a road.

A number of real deposits, soon to become mines, were found (King, 1973). John Jones, a wealthy grazier turned prospector, found the small 1.3 Mt Scotia deposit north of Kalgoorlie that was worked by Great Boulder Gold Mines who closed their Kalgoorlie gold mine and used the plant to process the ore. Metals Exploration discovered the Nepean deposit near Coolgardie in 1968, and WMC continued to find and develop deposits around Kambalda. Metals Exploration also found the world-class low-grade Mount Keith deposit with over 250 Mt at 0.6% Ni in 1969. The major mining companies were relatively unsuccessful; most of the early discoveries were made by prospectors working for junior companies. One exception was the Perseverance (now Agnew) deposit north of Leonora that was found by Australian Selection in 1971 with 33 Mt at 2.2% Ni and is still in production under BHP Billiton's Nickel West operations, which are also mining the Mount Keith deposit. The total amount of nickel mineralisation found at Kambalda now exceeds 100 Mt at a grade of around 3.5% Ni (Fig. 22).

Then there was Poseidon. In March 1969, Ken Shirley, a prospector working for this small exploration company, found a nickeliferous gossan over ultrabasic rocks near the small township of Laverton, 300 km NE of Kalgoorlie. He followed a discontinuous line of ultrabasics and found additional gossanous outcrops where the ultrabasic was in contact with a banded iron formation or jaspilite. He pegged the whole 8 km line of ultrabasics, and the company started routine exploration. Within a few months shallow drilling had shown indications of nickel sulphides and at the end of September 1969 Poseidon announced that they had found a substantial nickel deposit. The shares (only two million were on issue) had been trading around $1 and immediately jumped to $6 and then $12. Further news took them to $50 by the end of November. The company announced resources of 4 Mt at 2.4% Ni at the AGM just before Christmas, which took the shares to $130. They then rocketed to a peak of $280 in February 1970 before falling back through $50 by April and were only $39 by December 1970 (Sykes, 1978). The development of the mine took a couple of years and the orebody proved poorer and more complex than expected, leading to cash-flow and mining problems. Eventually the company were taken over by WMC and the mine was worked until 1990. At its peak the company was valued at over $700 million, but only about $250 million of metal was recovered. Following the recent discovery of additional mineralization, the mining of this deposit is scheduled for the future.

The Tasminex scandal in January 1970 was due to overoptimistic interpretation of minimal information during the Poseidon bubble. Tasminex had floated in October 1969 with two million shares at 25 cents. In early January 1970 these had reached $3.50 in line with the general optimism of the market. On 27th January 1970 the shares shot up to $18. The next day, following a newspaper interview with the chairman Bill Singline, a Tasmanian transport owner, they rose to $96 after he mentioned that 'massive sulphides' had been struck

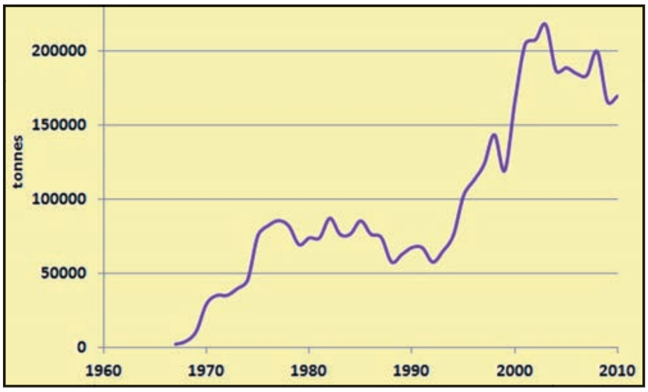


Figure 22. *Nickel production in Autralia (after Mudd, 2009).*

during drilling at Mount Venn 100 km east of Laverton and helpfully suggested that the find 'could be bigger than Poseidon' (Sykes, 1978). However, analysis of the sulphides found they were actually valueless massive pyrite with minimal nickel content and the share value rapidly retreated. A subsequent enquiry found that there had been substantial insider trading but the main culprit was grossly misleading and optimistic statements from company officials who were not professional exploration geologists.

The Poseidon boom so increased the pace of exploration that the WA Minister for Mines announced an indefinite ban on claim pegging from 3 February 1970, as there was such a backlog of unprocessed claims at the various Mining Registrar offices throughout the state. This led to a frantic search for new ground until the ban was lifted, with new regulations, on 5 June 1970 (King, 1973). On that day hundreds of geologists and prospectors were camped out throughout the bush waiting for the new regulations to be broadcast on state radio at 12 noon (Fig. 23). The amendments were modest; claim posts were 1.5 m high, instead of 1 m, and more trenches had to be dug along the sides of the claims. A frantic rush ensued with lines of rival claims intersecting and overlapping; one area was claimed by three companies who had approached it from different directions. Then the claims had to be registered on a first-past-the-post system at the relevant Mining Registrar's office. The resulting conflicting claims were mainly resolved by negotiation in the local Mining Warden's courts.

One astonishing fact to come out of the nickel boom was that nearly all the discoveries were made by prospectors finding surface gossans and not by geologists with all the geochemical and geophysical methods. The thick surficial cover and paucity of outcrop, coupled with highly saline groundwater, initially rendered 'modern' methods relatively ineffective and the traditional prospecting was the most successful method. However, many gossans were difficult to distinguish from the ubiquitous laterites and ironstones, and many promising blocks were carefully analysed and rejected as worthless.

***Figure 23**. Claim pegging at Yokradine Hills, near Lake Barlee, Western Australia.*

Away from nickel

Almost no one was looking for gold during the nickel boom. Gold was still only $35 per ounce, geochemical analysis was slow and costly, and the notion was that 'all the gold had been found'. Most nickel exploration geologists passed countless old gold mines and trials without a thought that there might be more to be found (Fig. 18 or 18a). However, there were a few enthusiasts who thought that payable gold could be found.

Other discoveries during this exciting period included the major Ranger, Jabiluka, Koongarra and Narbalek uranium finds in 1969 and 1970 in the Northern Territory's Arnhem Land. They are all unconformity-type deposits, forming at the contact between Lower Proterozoic basement and overlying Middle Proterozoic sandstones. Jabiluka and Koongarra remain undeveloped for various reasons, including the wishes of the local indigenous community; the former is close to the boundary of the Kakadu National Park. Narbelek was found by the small explorer Queensland Minerals and caused great stock market interest because of the very high grade of the ore (1.84% U_3O_8) and the few shares on offer. However, because of environmental and other concerns, the deposit was not exploited until 1979 when a four-month campaign extracted all the ore, which was treated over a longer period to produce 10,858 tonnes of U_3O_8 by 1988, more than any Australian uranium deposit to that time. The site has now been completely restored. Ranger was found by the medium-sized mining company GeoPeko and is now owned by Energy Resources Australia (ERA), a subsidiary of Rio Tinto. The controversial operation of a large open pit uranium mine in a World Heritage area adjacent to the Kakadu National Park, with a monsoonal climate and a long history of habitation by indigenous peoples has resulted in extremely close supervision and monitoring of the mine and associated facilities. Production began in 1981, and thrty years later Ranger was the second largest uranium mine in the world, with an annual output of 5240 t of U_3O_8. Reserves total 24 Mt at 0.1% U_3O_8.

Another type of uranium deposit, completely new to Australia, was found by WMC at Yeelirrie, near Wiluna in WA, in 1970, demonstrating the breadth of that company's expertise in exploration. The company had decided to look for uranium in WA using a sandstone-hosted model derived from mineralisation in the western USA. They realised that many of the salt lakes occupied earlier (Tertiary and Cainozoic) river channels that derived their sediments from the large expanses of Archean granite. Recently published national maps showed a number of radiometric anomalies, some associated with old channels. It was generally thought that the anomalies were due to potassium from the weathering of feldspars, but a field check showed that some were caused by uranium. Prospecting along a fence line discovered blocks of highly radioactive yellow carnotite ($K_2(UO_2)_2(VO_4)_2.3H_2O$). A total resource of 35 Mt was established at a grade of 0.15% U_3O_8 for a total of 52,500 tonnes U_3O_8. The deposit was formed in calcrete (calcium and magnesium carbonate) in an ancient palaeo-channel developed over millions of years. The carnotite ore zone is 3 m thick, about 9 km long and up to 1.5 km wide. It caused an immediate rush to survey all salt lakes with radiation detectors. A number of similar, but smaller deposits were found, but at the time the Australian Government's policy of only three uranium mines ruled out any development while the existing mines were in operation. The deposit, still unmined, is now owned by BHP Billiton.

A new area of heavy mineral sands containing economic levels of ilmenite used in paint manufacture, as well as zircon and rutile, was found by chance at Eneabba, north of Perth, in September 1970 by a farmer drilling post holes. He noticed that the sand from excavated holes was black and dense, so he contacted local ilmenite mining companies, such as Western Titanium, who were based around Capel, south of Perth. Within a short time a major pegging rush began with one company alone pegging over 1000 claims and flying a radiometric survey over several hundred kilometres of coast. The deposit was in high-level, fossil shorelines up to 20 km inland from the coast, where the local topography in late Tertiary to early Pleistocene times had caused longshore drift to deposit the denser heavy minerals in embayments (Shepherd, 1990). The deposit was rapidly drilled out and consists of several parallel high-grade lenses over a 5 km long zone containing around 30 Mt of recoverable heavy minerals (Fig. 24).

A large carbonatite (alkaline igneous intrusion) was found in 1967 by Utah Development at Mount Weld 35 km south of Laverton in WA and drilled in the early 1980s by Union Oil as a phosphate, niobium and tantalum prospect (Duncan and Willett, 1990). It was later taken up by Lynas Corporation, which currently claims it is 'the richest known deposit of rare earths in the world' with a total resource of 1.4 Mt of REO (Rare Earth Oxides) at grades of up to 14% in zones within the 3 km diameter intrusion.

Figure 24. Drilling to prove the ilmenite-rich heavy mineral sands at Eneabba.

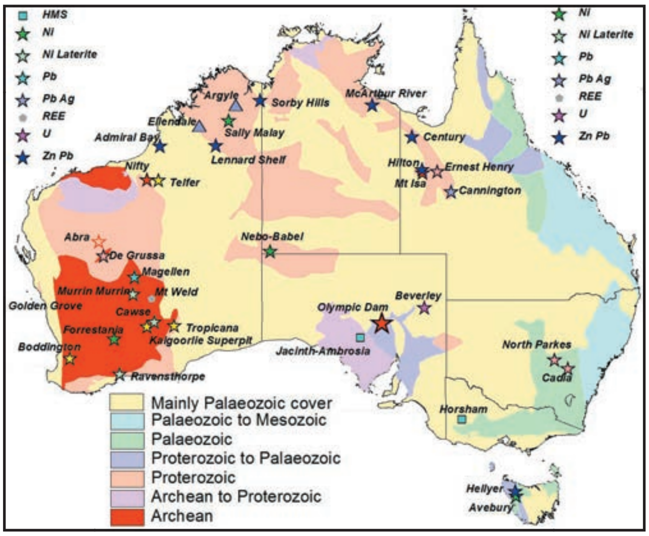


***Figure 25**. Significant mineral discoveries since 1975.*

The major Elura lead-zinc-silver deposit was discovered by Electrolytic Zinc Corporation in 1973 about 40 km NNW of the old mining town of Cobar in central New South Wales. This enigmatic deposit consists of several semi-vertical, pipe-like massive sulphide bodies with a vertical extent of up to 1000 m in Lower Devonian meta-siltstones (Schmidt, 1990). There are no igneous rocks in the area. The main sulphide is pyrrhotite, which causes a strong magnetic anomaly to act as a drill target. The pre-mining resource totalled around 45 Mt with grades of 8.5% Zn, 5.3% Pb and 69 g/t silver. The mineralisation is now thought to be the result of overpressured basinal fluids being released during metamorphism and depositing minerals in low-pressure zones within faulted anticlines with some interactions with the host rocks. Mining started in 1983 and after passing through various ownerships the deposit, now called Endeavour, was bought in 2010 by Toho Zinc of Japan.

From 1975 to 2011

This period has been dominated by the new gold rush, the ever-increasing output and export of iron ore, major copper and lead-zinc discoveries in Queensland and New South Wales, and the discovery and development of Olympic Dam – the world's largest single mineral deposit. There was also a spate of developments of surface-mined nickel laterite deposits, with only one achieving continued production, and a group of high-grade nickel deposits (Fig. 25). And a world-class diamond deposit was discovered in the Kimberley.

Historically Australia had been considered 'Terra Nullius' or belonging to nobody before the arrival of European settlers. However, following the historic Mabo ruling of 1992 which recognized Native Title, many groups of indigenous peoples asserted their right to be consulted on the development of ancestral areas. The Mabo case has caused additional responsibilities for mining companies to research possible ownership of land containing mineral deposits by traditional peoples and to work with them and the State Governments to provide suitable employment and other opportunities. Companies also need to work with the indigenous population to avoid heritage sites.

Return to gold

The rise in the world gold price from $35 per ounce in 1972 to $600 /oz by 1980, coincided with development of rapid, reliable, low cost and high-precision analytical methods for gold, with detection levels down to 2 parts per billion (ppb). Along with a general depression in base metal prices, mining companies turned towards concentrating on gold exploration. It is telling that a major publication on Australian economic geology, published in 1975, contained just 10 pages on gold in WA but 100 pages on nickel (Knight, 1975). The gold section was entirely on existing deposits, with no new finds mentioned. The next volume, published in 1990, devoted 120 papers (out of 261) specifically to gold, and mainly to new deposits, illustrating the rapid rise in gold development (Hughes, 1990).

The first major gold deposit to be discovered was Telfer in the remote Patterson Ranges of WA 400 km east of Port Hedland (Dimo, 1990). Newmont Mining, an American company with large gold mines in Nevada, was informed of a large gossanous area in Proterozoic sediments, possibly of copper, by a prospector who had found the area in 1970. However, he did not peg the area and did not suspect that it contained gold, when the low price meant that no Australian company was interested. However, Newmont, being a gold mining company, did consider gold and in 1972 visited the area and pegged it as a gold prospect. A major open-pit mine was opened in 1977 and produced 6 M ounces of gold to 2000, when the presence of minor copper at depth made it uneconomic. The processing operations were revised, and the mine reopened in 2007 as an open-pit mine with a final planned depth of 650 m and an underground operation working ore shoots that extend beyond 1500 m depth. Current reserves are around 400 Mt of openpit ore containing 11M oz gold and 400,000 t copper, along with 37 Mt of underground ore containing 2M oz and 120,000 t copper. There are also extensive potential resources.

From the late 1970s onwards a new mining industry was rapidly developed in Western Australia based on opening increasing numbers of small to medium sized open-pit gold mines (Woodall, 1990). These were located using soil sampling and shallow, reverse-circulation drilling around old mines that had worked quartz veins and shear zones with high-grade gold at 10 g/t; the new deposits contained low-grade veins and disseminated mineralization. Very selective, but large-scale, open-pit mining and strict grade control, coupled with the use of the new carbon-in-pulp technique for recovery of the fine-grained gold, was used to achieve economic operation from deposits with grades down to 1 ppm. A number of the mines, such as the Plutonic mine north of Meekatharra, were subsequently extended as underground operations using spiral decline ramps for access. Total Australian gold production (mainly from WA) rose rapidly from 18 tonnes in 1981 to 313 tonnes in 1997 (Fig. 27). The remaining deep, narrow-lode mines on the famous Golden Mile at Kalgoorlie (Lake View and Star, North Kalgurli and Great Boulder) had all closed by 1974 leaving only the large-scale, underground block-caving Mount Charlotte operation.

The rising gold price renewed interest in the area in the late 1970s, and in 1983 a series of small open pits were opened. A flamboyant entrepreneur, Alan Bond, bought controlling interests in every key lease in 1987, but by 1989 financial problems forced him to sell to

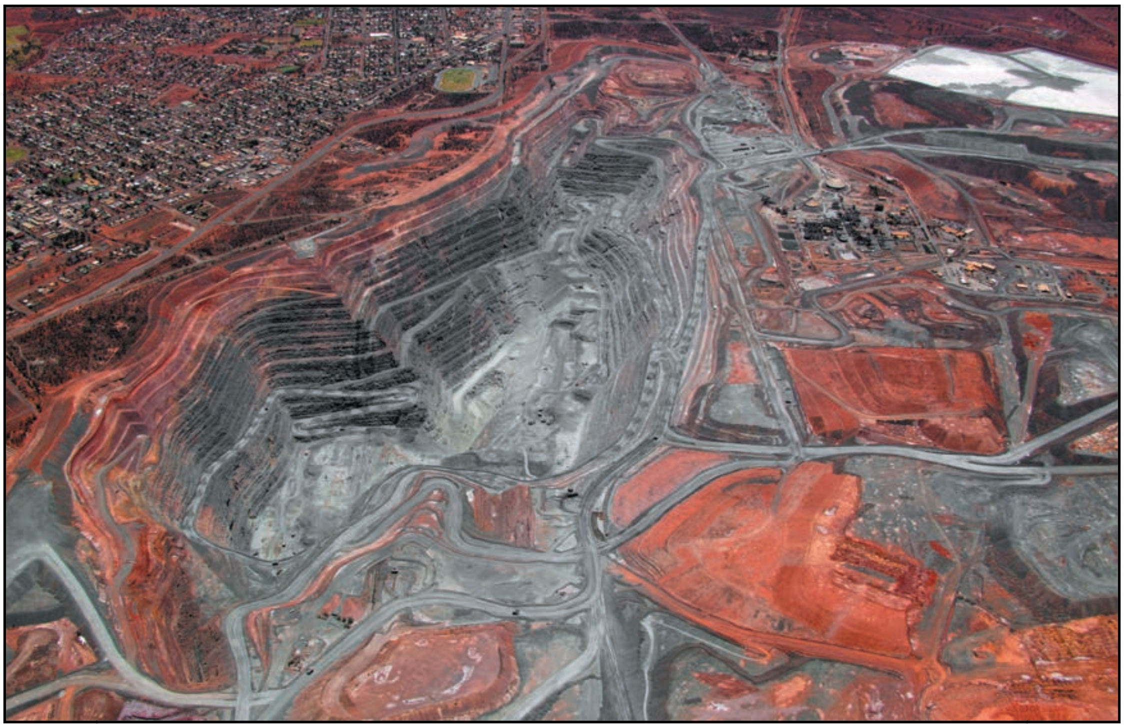


***Figure 26**. The Superpit that is now extracting gold from the entire zone of veins at Kalgoorlie; the town is at top left, and the mineral processing plant and waste tips are on the right (photo: KGMA).*

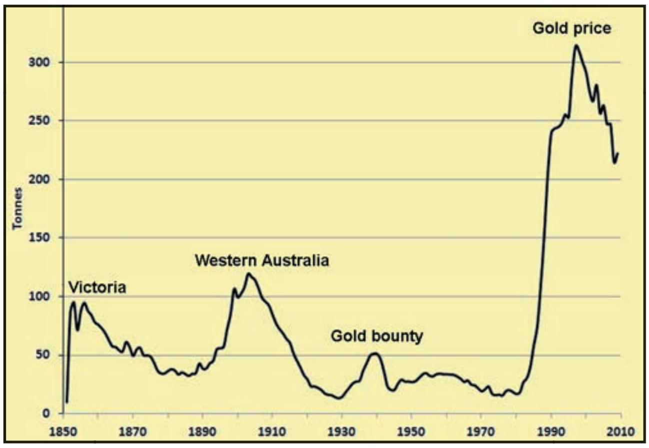


***Figure 27**. The peaks of annual gold production in Australia (after Mudd, 2009).*

Kalgoorlie Consolidated Gold Mines (KCGM), a joint venture between Homestake Gold of Australia and Gold Mines of Kalgoorlie (GMK), a WMC subsidiary. KCGM developed the Superpit, a major open-pit that encompasses a large area of the Golden Mile and will eventually be 3.8 km long, 1.4 km wide and over 500 m deep (Fig. 26). Current operations mine 85 Mt of rock per year, including 12 Mt of ore, to produce up to 800,000 oz (22.7 t) of gold. In 2001 Homestake merged with Barrick and in 2002 GMK was taken over by Newmont. The Golden Mile produced its 50 millionth ounce of gold (over 1400 tonnes) in 2003. The Superpit is scheduled to continue in production until 2021.

In 1979 the Geological Survey of Western Australia discovered a gold anomaly in soil during a routine regional mapping programme near Boddington in the Darling Ranges 100 km southeast of Perth. The area is in the Saddleback Greenstone Belt of the Western Gneiss Terrain. It had previously been explored for bauxite deposits, and Reynolds Australian Mines Pty re-analyzed, for gold, some of the old bauxite exploration vacuum-drill samples, and discovered gold in surficial laterites and clays overlying a low-grade, porphyry-style, gold-copper deposit. Without doing any additional drilling, a gold resource was defined. Gold deposition was at a redox front at or near the Tertiary water table (Symons *et al.*, 1990). Open pit resources of 60 Mt at 1.6 g/t gold made this deposit one of the largest discovered up to that time. Mining the surficial deposit began in 1987 and was completed in 2001. After a prolonged hiatus, the underlying primary deposit, now owned by Newmont Mining, started operations as a major open pit mine in July 2009, and is producing at an annual rate of up to 1M ounces of gold along with 30,000 t of copper. The pit will eventually be over 4 km long, 1 km wide and up to 700 m deep. Resources are stated at over 20M oz of gold and over 1 Mt of copper.

***Figure 28**. A 350-tonne truck from the Superpit, in the St Barbara's Day parade in Kalgoorlie (photo: D Graham).*

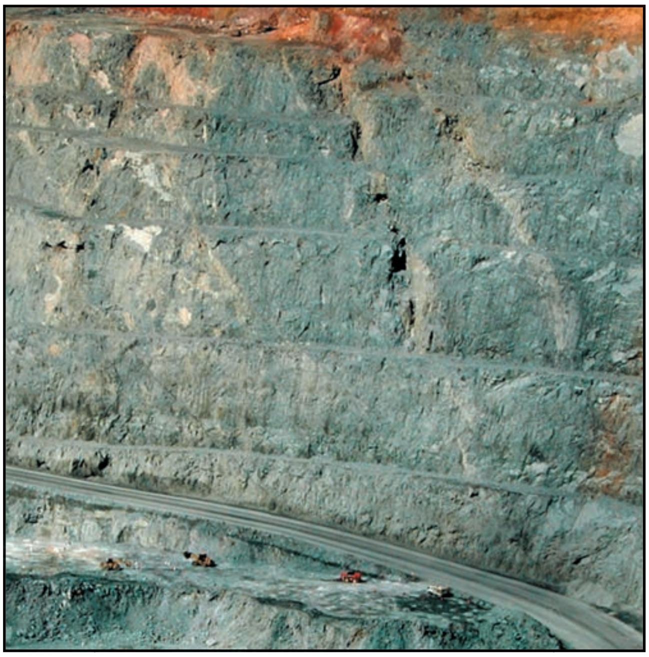


***Figure 29**. Old workings on gold veins exposed in the end wall of the new Superpit at Kalgoorlie.*

Interestingly over 75% of Archean gold (~120M ounces) has been produced from the Norseman-Kalgoorlie Belt which only makes up a small proportion of the total Yilgarn greenstone area (Huleat and Jaques, 2005). The Southern Cross Belt has produced 10M oz; the Leonora-Wiluna Belt 12M oz and the Laverton Belt 25M oz (Fig. 30). Significant new discoveries are still being made. In 2005 a joint venture between Anglo Ashanti and Independence Mining found the major Tropicana deposit southeast of Laverton at the northern end of the Frazer Mobile Belt; a previously unprospected area of late Proterozoic rocks striking northeast at the southeast margin of the Yilgarn craton. The series of near-surface deposits at Tropicana now contain over 88 Mt of resources at a grade of 2.3 g/t Au for a total of 6.4M oz of gold with open ended extensions at depth and along strike in an area of 15,000 km^2 over a length of 330 km. It is expected that other gold deposits will be discovered in what is now considered to be a new gold province. Mine construction has recently commenced, with the first gold pour expected in mid 2013. A small company, Gold Road Resources, currently has much of the poorly explored Yamarna Belt, northeast of Laverton, under licence and has made several small discoveries associated with a major shear zone recognized during recent state mapping.

***Figure 30**. One of the many worked-out open pit gold mines in the Leonora-Wiluna mineral belt.*

The intensive exploration for gold since the 1980s, and the development of many open pit mines throughout the Yilgarn Shield, has led to a much greater understanding of its regolith – the veneer of post Archean (mainly Cainozoic) material up to 30 m thick on top of the ancient rocks. What was termed undifferentiated overburden in the early 1970s is now recognized as the product of a complex interaction of weathering and erosion, with many chemical processes that are either complete or ongoing. The work of Charles Butt at the CSIRO and Richard Mazzuchelli, chief geochemist of WMC, coupled with the development of new analytical techniques, lower levels of detection and computerized statistical analysis, enabled the detection of more subtle targets. Now, the full range of GPS positioning, geochemistry, air- and satellite-borne multi-spectral mineral analysis and 40 years of experience are employed to understand the regolith for mineral exploration and environmental purposes.

Another trend in Western Australia was the recognition that there were extensive deposits of lateritic iron-oxide nickel-cobalt mineralization overlying many of the ultrabasic rocks of the greenstone belts (Fig. 31). Lateritic nickel had been largely ignored during the early nickel boom of the 1960s and 70s as the high capital costs of the complex processing plants deterred significant interest. A successful laterite deposit was mined from 1974 to 1993 at Greenvale, in northern Queensland, by Metals Exploration and Freeport on reserves of 40 Mt at 1.57 % Ni and 0.12 % Co; it had a refinery at Townsville on the coast, and the mine site is now fully restored. However, the availability of cheap sulphuric acid from the WMC nickel sulphide smelter at Kalgoorlie and natural gas from the offshore Northwest Shelf, led to prospects being developed at Murrin Murrin, Cawse and Bulong, all northeast of Kalgoorlie. The high-pressure acid-leach process was used, but the high capital cost of the equipment (which operates at 250°C and 45 atmospheres pressure) and severe and prolonged problems with development, as well as a fluctuating nickel price, saw only the Glencore-owned Murrin Murrin mine near Leonora survive. Even this has yet to achieve its planned output of 40,000 t of nickel and 5000 t of cobalt; it is currently producing around 30,000 t of nickel per year from reserves of 196 Mt at 1.05% Ni and 0.078% Co.

Another laterite deposit at Ravensthorpe on the south coast of WA was developed by BHP Billiton from 2004 to 2008 as an open pit mine with a capacity of 50 000 t/yr nickel. After costing over $2000M, it was unable to achieve economic production at the then-depressed nickel price, and was closed after a year of operation. The project was bought by First Quantum Metals for $340M in 2010, and commercial production commenced in late 2011. It is estimated that the mine will produce 28,000 t/yr over its expected mine life of at least 30 years.

After a hiatus of almost 20 years with no significant new nickel sulphide discoveries in the Yilgarn craton, a junior company, MPI Minerals, discovered the very high-grade Silver Swan deposit north of Kalgoorlie in 1995 with an initial resource of 650,000 t at 9.55% Ni. The deposit was discovered after reassessing the results from previous explorers. Production started in 1997, as the first of a number of small, but generally high-grade, nickel sulphide deposits, especially in the Southern Cross area. There, Western Areas NL have over 5 Mt of reserves at a grade of around 3.3% Ni in the Flying Fox, Spotted Quoll and Diggers deposits. Much higher grades occur in some of the deposits.

Western Mining Corporation discovered a number of new deposits in the Kambalda area from the mid 1990s (Fig. 32), but then divested its numerous Kambalda

***Figure 31**. Lateritic caprock, widespread in Western Australia.*

***Figure 32**. The Silver Lake nickel mine near Kambalda.*

mines after 2000 to a number of junior companies such as Independence and Panoramic who have continued to develop them and have discovered a number of extensions or new ore bodies. Smaller nickel deposits have been developed at Savannah (formerly Sally Malay) in the Kimberleys, in an unusual remobilized skarn in Palaeozoic rocks at Avebury (near Zeehan in Tasmania), and at Radio Hill near Karratha in the Pilbara, where an innovative biological leach process to extract nickel and copper from this low-grade deposit is being tested. The last two are currently on care and maintenance pending an upturn in the nickel price. A new prospective province has recently been announced in central Australia where the Nebo-Babel occurrence in late Proterozoic rocks of the Giles complex in the Musgrave Block near Wingellina was found by WMC in 2000. One early drill hole intersected 26 m at 2.5% Ni, 1.8% Cu and 0.4 g/t PGE (platinum group elements) giving promise that this remote area could achieve major significance. A preliminary resource was reported in 2007 of 393Mt at 0.3% Ni, 0.3% Cu and 0.18g/t PGE (Geoscience Australia, 2012). Exploration by BHP Billiton and junior companies is continuing.

Copper, lead and zinc

Following the Kambalda nickel discoveries and the subsequent surge in exploration, attention also turned to another common type of deposit in the Canadian Shield – the VMS copper-zinc deposit exemplified by the giant Kidd Creek site near Timmins, Ontario. These deposits are generally hosted in acid volcanic rocks, usually near a contact with basic volcanic rocks as described in the seminal report by Sangster (1972). A number of mainly international companies started looking in the ‘greenstone’ belts of the Yilgarn and Pilbara cratons for rhyolites and other acid volcanic rocks. This work was assisted by the ongoing remapping of the shield by the state geologists as earlier mapping had not differentiated the various components of the greenstone belts. A few small deposits were known, such as Whundo (Figs. 33 and 34), Whim Creek and Mons Cupri in the Pilbara and Murrin Murrin in the Yilgarn (Reynolds *et al.*, 1975), but the acid volcanic rocks were not delineated on airborne magnetic maps, unlike the magnetite-bearing basic and ultrabasic rocks associated with nickel deposits. The Pilbara VMS deposits are some of the world’s earliest ore deposits known, with the small North Pole baryte deposit dated around 3490 Ma and the Big Stubby lead-zinc-baryte deposit near Marble Bar occurring in rocks dated at 3472 Ma (Fig. 24).

A small company, Aztec Exploration, recognized gossans at outcrop at Golden Grove near Yalgoo in the northwest Yilgarn in 1971, and by the mid-1970s a joint venture with Amax and Electrolytic Zinc had established resources of 15 Mt at 3.4% Cu hosted in a thick rhyodacitic sequence (Smith, 2003). Low metal prices caused development to be delayed until 1990, but the separate Gossan Hill copper and Scuddles zinc mines, now owned by Minmetals Resources of China, are currently producing at a rate of 30,000 t of copper and 75,000 t of zinc per year from copper resources of 26.9 Mt at 2.6% Cu and 0.5% Zn and zinc resources of 9.7 Mt at 11.7% Zn 1.0% Pb and 0.5% Cu with significant silver and gold.

***Figure 33**. Copper-zinc-rich gossan in bleached and weathered surface rock at Whundo, in the Pilbara.*

The gossan above the small Teutonic Bore deposit near Leonora was discovered by Carpenteria Exploration in 1974. It was drilled by Australian Selection in 1976 to reveal a small high-grade VMS deposit with resources of 2.2 Mt at 3.5% Cu, 11.1% Zn, 0.9% Pb, 52 g/t Ag and 0.2 g/t Au at the contact of acid and basic/intermediate volcanic rocks. This was largely mined out by BP / Mt Isa Mines between 1980 and 1985. The area was owned by Jabiru Metals who found two additional lenses of mineralisation of similar size and grade (Jaguar and Bentley) that are currently in production. The new owner is Independence Group, a mid-size Western Australian company. Recently another WA exploration company, Sandfire Resources, announced the discovery in 2009 of a very-high-grade copper-gold VMS deposit at DeGrussa near Meekatharra, but in Paleoproterozoic volcanic and sedimentary rocks of the Bryah Basin, located north of

***Figure 34**. Drilling to prove nickel reserves at Whundo.*

the Yilgarn craton. Initial drilling results included such outstanding figures as 9.1 m at 34.9% Cu and 3.3 g/t Au and 53.1m at 17.3% Cu and 2.5 g/t Au from chalcocite (Cu_2S) in the supergene zone near the surface. The mine began production of Direct Shipping Ore (requiring no on-site treatment) in February 2012 from the high-grade supergene zone in the open pit. A decline 1250 m long reached the massive sulphide ore at a depth of about 200 m in March 2012, showing the rapid pace of development. Total current resources of open-pit and deep-mine mineralization are 14.33 Mt at 4.6% Cu and 1.6 g/t Au. Exploration for additional VMS deposits is continuing at DeGrussa and by other companies in many other parts of the Yilgarn and Pilbara cratons.

The very large and complex Sedex-type Abra deposit was discovered in mid-Proterozoic rocks of the Bangemall Basin, between the Yilgarn craton and Hamersley, during a basin-wide search for base metal mineralization by Amoco Minerals in the mid-1970s, in response to the recognition that the rocks are of similar age and composition to those hosting the major Mount Isa deposits in Queensland (Boddington, 1990). Initial regional geochemical sampling proved disappointing, until GeoPeko joint ventured into the prospect and drilled a hole in 1981 into a discrete magnetic anomaly. There they intersected a wide zone of base metal mineralisation under 270 m of barren cover, including 27 m at 6.1% Pb, 194 m at 3.1% Pb and 19 m at 1.1% Cu with 3.68 g/t Au. Significant barium and iron oxide mineralisation is also present in the thick, hydrothermally altered, sedimentary sequence. Subsequent drilling has outlined large resources of 93 Mt at 4% Pb and 10g/t Ag and 14 Mt at 0.6% Cu and 0.5g/t Au. The site is now owned by Hunan Nonferrous Metals Corporation of China, but is yet to be developed.

The Magellan lead deposit, possibly the largest lead carbonate deposit in the world, was discovered in 1993 north of Wiluna. Mineralization is in a quartz sandstone and siltstone formation of the Proterozoic Yerrida Basin, situated between the Yilgarn craton and the Hamersley. It consists of zones of secondary lead carbonate (cerrusite) and sulphate (anglesite), and is interpreted to have originally replaced a carbonate-hosted base-metal deposit which became enriched in secondary lead minerals through prolonged and extensive weathering of primary base-metal sulphide minerals. Although mining commenced in 2005, the deposit is currently on care and maintenance, due in part to reported issues related to lead contamination at the Esperance port in 2007 and at the Port of Fremantle in 2010. It is currently owned by Ivernia of Canada.

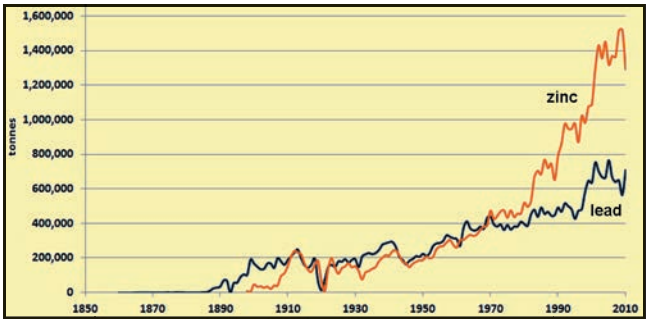


***Figure 35**. Australian lead and zinc production to 2010 (after Mudd, 2009).*

The large Admiral Bay lead-zinc deposit was accidently discovered in 1981 when an oil exploration hole intersected a thick sequence of mineralized Ordovician carbonate rocks at a depth of 1280 m under a thick cover of Silurian and younger rocks in the centre of the Palaeozoic Canning Basin in northwestern WA (Connor, 1990). The mineralisation is associated with the major Admiral Bay growth fault. Subsequent drilling by CRA from 1986 to 1992 outlined a large resource with 10-20 m thick, upper zinc-dominant and lower lead-dominant, zones over a length of 20 km along the fault trace. The deposit is now owned by Kagara Zinc, which has established a resource of 72 Mt at 3.1% Zn, 2.9% Pb, 18 g/t Ag and 11% Ba; Kagara had intended to sink an exploration shaft, 6.7 m in diameter and 1400 m deep, to enable detailed underground reserve drilling to be carried out, but is currently in administration. The deposit is of the Mississippi Valley Type (MVT) class of platform carbonate-hosted lead-zinc deposits. Its discovery sparked a worldwide check of oil drill holes into carbonate reservoirs that might have also intersected mineralization, as the pale brown, iron-poor sphalerite might easily be missed in drill mud chippings.

Another large MVT province occurs on the northern edge of the Canning Basin in Devonian carbonates of the Lennard Shelf in the Kimberley District of WA. The area contained pre-mining zinc-lead resources of 41 Mt at 7.9% Zn and 3.2% Pb. A number of companies have worked several deposits in the area since the 1970s but all faced erratic and generally depressed base metal prices and difficult mining conditions in this remote area, so production has been sporadic. The deposits are now owned by Meridian Minerals which has established resources of 17.7 Mt at 5.5% Zn and 4.0% Pb. Meridian has recently been taken over by Northwest Nonferrous of China.

In the Phanerozoic Bonaparte Basin, located in the far northeast of WA, Sorby Hills is another MVT project. Although discovered in 1971, it still has not been developed. The current proposal is for open-cut mining to commence in 2013 on six of the thirteen separate but adjacent carbonate-hosted, near-surface lead-silver-zinc deposits. Current ownership is a 75:25 joint venture between KBL Mining Ltd (an Australian company) and China's largest silver and lead smelter, Henan Yuguang Gold and Lead Company.

Kimberley diamonds

Australia is not famous for its gem minerals, except for precious opal, which has been mined for many years. Coober Pedy was the earliest field found, in 1915, but was followed by Andamooka in northern South Australia, Lightning Ridge in New South Wales and

Figure 36. The open-pit at the Argyle diamond mine.

several minor localities in Queensland. Australia now produces around 95% of world gem opals. Coober Pedy is best known for white opals and Lightning Ridge for black opals. The opals formed by dissolution of silica during long periods of weathering of Cretaceous and other sedimentary rocks in the Tertiary period and its reprecipitation in nodules that gradually hardened over a long time. They occur as irregular patches and lenses of common opal, and rarely of precious opal. They are generally mined by individuals or small groups due to their irregular and unpredictable occurrence. Coober Pedy is famous for the underground miners' houses and churches that are favoured as escapes from extremely high temperature in summer.

Small numbers of alluvial diamonds have been recovered in New South Wales and elsewhere. Then the Argyle diamond pipe was discovered near Kununarra in the Kimberleys in 1979 after a seven-year search by Ashton Mining and then CRA (later Rio Tinto). The Kimberleys were chosen due to their similarity to areas hosting many African diamonds (Kimberley in South Africa and the Kimberleys of Western Australia were both named after the English Earl of Kimberley who was a prominent politician in late Victorian times). Panning of stream sediments was used as the main exploration technique. A number of small diamonds were found, leading to the discovery of several lamproite pipes in the Smoke Creek near Lake Argyle. In October 1979, the main Argyle AK 1 pipe was found, and the Argyle Diamond Mine was commissioned as an open pit in December 1985 (Fig. 36). The mine quickly became the world's largest diamond producer with outputs in excess of 30 M carats per year. However, only 5% were gem diamonds; the rest were brown and black industrial diamonds, known as bort. The mine soon became famous for producing almost the entire world output rare pink diamonds (described by the company as beyond rare). The mine's diamonds also tend to be small, so the larger pink diamonds, which make up less than 0.1% of the gem diamonds, command high prices in an annual tender process. In 2010 only 55 diamonds were available. A 12.76 carat pink diamond (the largest to date and valued at over $1M) was found in February 2012. The Argyle open pit is scheduled to close when an underground block-caving operation is developed for full production at 9 Mt of ore per year from 2013, extending the mine life to 2019 and beyond.

The Ellendale mine is another diamond mine in the Kimberley. Extraction from several lamproite pipes commenced in 2002 by Kimberley Diamond, and in 2007 the mine was sold to Gem Diamonds, a London-listed company. Ellendale is one of the world's best sources of highly prized fancy yellow diamonds, all of which are sold exclusively to the luxury jeweller Tiffany. The mine produced over 766,000 carats during its first five years of operations.

Olympic Dam – the mega-deposit

Western Mining Corporation, already known as leaders and innovators in Australian exploration, startled the mining world in November 1976 by announcing the discovery of a major copper deposit on Roxby Downs Station in South Australia. WMC had been spending an average of 56% of its profits on exploration through the 1960s and 1970s and was well known in the industry for encouraging research and supporting geologists to take higher degrees in areas relevant to their work. They had already been looking for copper since the early 1960s, with ventures in the Kimberleys, in the remote Warburton Ranges on the NT/WA/SA border and for Copperbelt-style deposits in cupriferous shales in the Hamersley Ranges. In 1969 a geologist, Doug Haynes), was given leave to study for a PhD, taking as his research the release of copper from basalt when magnetite is oxidised to hematite. By 1972 WMC had an exploration tool that enabled them to select potential copper-bearing areas. The idea was that oxidation and alteration of large volumes of suitable basalt might release copper that could migrate up faults into reducing sedimentary basins and deposit either syngenetic copper on the sea floor or epigenetic copper in suitable buried host rocks, such as carbonates (Fig. 37).

Figure 37. Endless and nearly flat desert in South Australia, beneath which was found the giant Olympic Dam orebody.

The Stuart Shelf in South Australia was chosen as a test area because it contains basalts in the southern part of the shelf that might underlie NeoProterozoic to Cambrian sediments on the shelf. The shelf also hosted a number of small sediment-hosted copper occurrences, as at Mount Gunson. WMC used the published government gravity and aeromagnetic surveys to indicate areas of denser magnetic rocks that could be basalts able to act as source rocks. An academic geologist, Tim O'Driscoll, had developed a system of structural analysis to reveal major tectonic lineaments. The Mount Gunson area showed interesting gravity and magnetic anomalies combined with a major WNW/NNE lineament intersection, but an even stronger one was found to the north in the Andamooka area on Roxby Downs Station (O'Driscoll, 1986).

A drillhole location was chosen, using the Olympic Dam (constructed during the 1956 Melbourne Olympic Games) as a water source (the next drill site was at Appendicitis Dam!). The hole, RD1, was drilled through 335 m of Late Proterozoic horizontal limestones, sandstones and shales before ending, on 30 July 1975. in 76 m of a dark-coloured breccia full of hematite but with no visible copper mineralization. This was initially thought to be altered basalt stripped of copper, and, while disappointing, at least proved the theory was correct. As there appeared to be no copper, the breccia was not analysed as a priority so two months elapsed before the results were completed. These came as complete surprise as they revealed that it contained an average of 1.05 % copper. The copper was present as fine-grained bornite, similar in colour to hematite, rather than as yellow chalcopyrite. However three more holes were drilled, and these found no copper. The fifth hole was similar to the first, but the next four were barren or of very low grade. The decision to drill the tenth hole was typical of WMC management at the time in supporting their exploration team and trusting to their judgement. The gamble paid off when RD10 intersected 170 m of 2.12 % copper. This was announced to the world at the WMC AGM in November 1976. Early in 1977, further analysis revealed completely unexpected and very significant contents of gold and uranium. This caused great problems for the anti-nuclear, labour, state government then in power.

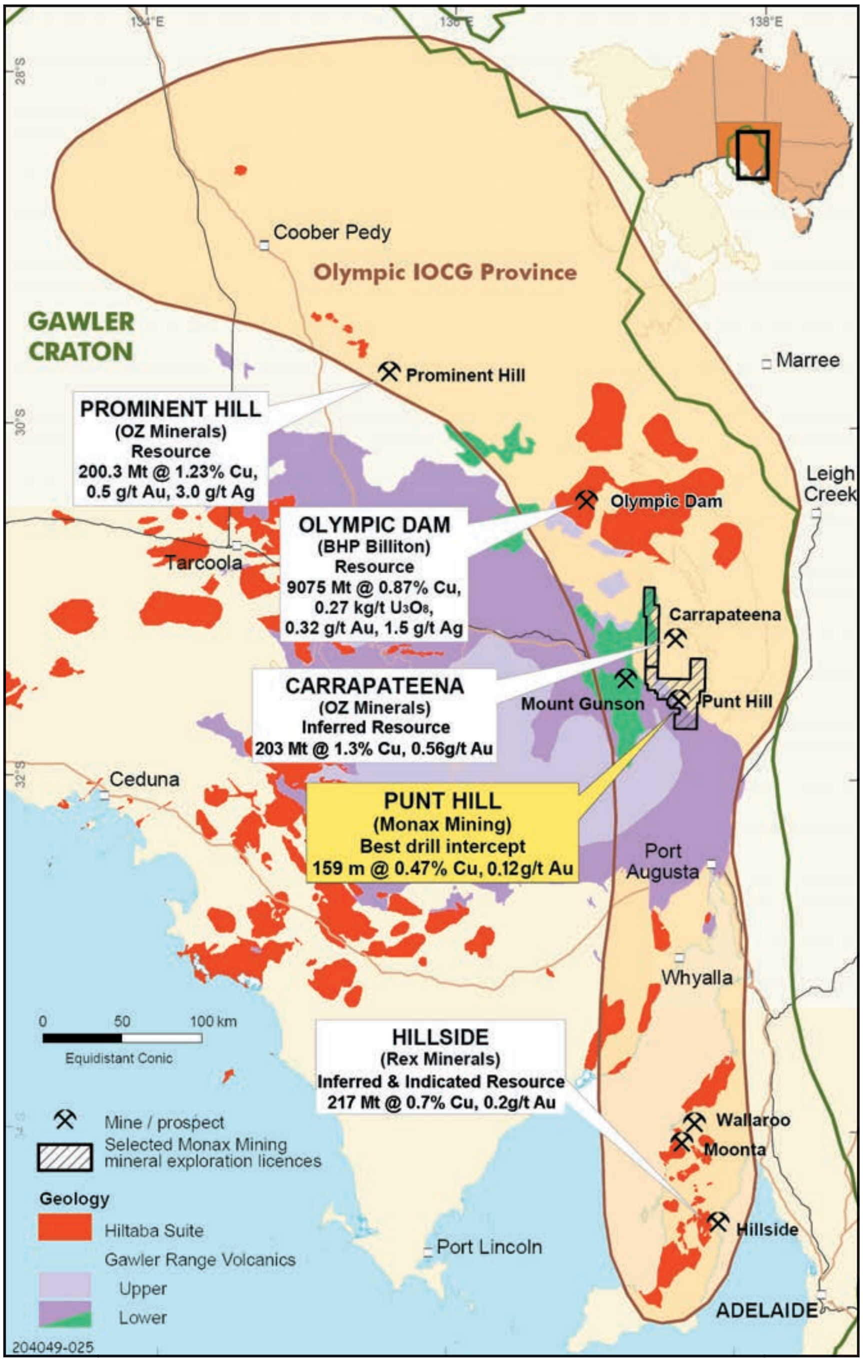


Figure 38. Geology of Olympic Dam and adjacent orebodies, (after Monax Mining).

Drilling continued with more misses than hits, but RD17, 19 and 20, drilled 2 km east of Olympic Dam, proved significant thicknesses of high grade mineralisation and confirmed the major scale of the discovery. BP entered a joint venture in 1979 to acquire 49% of the project by spending \$300 million and in the same year the labour state government was defeated by the pro-mining liberal party in an election dominated by the Olympic Dam development. The Whenan exploration shaft, just 6.5 m by 3.5 m and named after Ted Whenan who had drilled RD1, was started in 1980 to provide access to the orebody for bulk samples and underground development drilling. In 1982 the first resource estimate was released of 2000 Mt at a grade of 1.6% Cu, 600 ppm U_3O_8, 0.6 g/t Au and 3.5 g/t Ag. The mine development continued to be a contentious issue in South Australia, particularly due to the planned production of uranium, and there were demonstrations at the mine. However, both major parties supported the mine as a major contributor to South Australia's economic development for many years to come.

The decision to develop the deposit was taken in December 1985 and construction started in March 1986. The mine and processing plant were commissioned in 1988 at an initial rate of 45,000 t Cu, 1700 t U_3O_8 and 70,000 oz Au. This has been progressively increased over the years and the mine is currently operating at around 10 Mt/yr of ore at a grade of 1.98% copper and 540 g/t U to produce 220,000 t/yr copper, 4000 t/yr uranium, 80,000 oz/yr gold and 800,000 oz/yr silver.

Exploration over the years has continued to increase the overall resources of the deposit, which currently stand at about 9000 Mt containing around 80 Mt Cu, 2.45 Mt U_3O_8 and 93M oz Au. It is the largest uranium deposit in the world by far, and is the fourth largest deposit of both gold and copper. The deposit is largely confined to a hematitic breccia developed in sedimentary rocks associated with a NW-trending graben along a major crustal lineament. The rocks are extensively altered by hydrothermal fluids that may have been focused by the lineament (Roberts and Hudson, 1983). Apart from large amounts of iron, copper, uranium, gold and silver, the deposit also contains elevated amounts of fluorine and rare earth elements such as lanthanum and cerium.

WMC was taken over by BHP Billiton in 2005, and plans have recently been submitted to expand output further by developing an open pit mine producing 40 Mt/yr of ore to yield 500,000 t Cu, 15,000 t/yr U_3O_8, 500,000 oz/yr Au and 2.9M oz/yr Ag for well over 50 years. The open pit will require stripping more than 300 m of barren overburden to expose the ore and will eventually be 3 km long, 2.8 km wide and 1 km deep.

The discovery of such a large and unusual deposit has engendered much research both into its origin and as to whether other similar deposits exist. There is a general consensus that, among other factors, the Hiltaba Granite suite, major intersecting crustal lineaments, tectonic and hydrothermal brecciation and long-lived or successive pulses of basinal brines and metamorphic fluids have all played significant roles in the location and formation of the deposit. The Olympic Dam discovery led to the recognition of a new worldwide class of Iron Oxide Copper Gold (IOCG) mineral deposits. They are a varied group with hematite or magnetite as the iron oxide and all have significant contents of rare earths though not all have significant contents of uranium, copper or gold.

Several similar deposits have recently been found in the same general area and setting in South Australia (Fig. 38). The most important are the Prominent Hill and Carapateena deposits. Prominent Hill was discovered by the junior company Minotaur Exploration in 2001 under 100 m of cover and put into production by OZ Minerals as an open pit in 2009. Underground mining will commence in 2012. Ore reserves in June 2011 were 72.3 Mt at 1.13% Cu, 0.64 g/t Au and 3.03 g/t Ag, with total resources of 214.9 Mt at 1.23% Cu, 0.5 g/t Au and 3.5 g/t Ag.

***Figure 39**. Australian copper production (after Mudd, 2009).*

The Carapateena deposit was discovered in 2005 by the small exploration group RMG, using funds from PACE, the SA Government drilling incentive. The top of the cylindrical deposit is 470 metres below surface and the deposit extends over a vertical depth of at least 1000 m. Teck Resources drilled 33 holes totaling 45,504 m to delineate an inferred resource of 203 Mt at 1.31% Cu, 0.5 g/t Au, 6 g/t Ag and 270 ppm U_3O_8 for the southern part of the partly explored deposit. The best hole intersected a spectacular 905 m at 2.17 % Cu and 0.89 g/t Au from a depth below surface of 506 m. The deposit was bought by OZ Minerals in 2011 who intend to develop it in the near future. A recent press release (15 February 2012) by OZ Minerals cites a drill hole intercept of 1060 m at 1.88% Cu, 0.69 g/t Au, 7.4 g/t Ag and 204 ppm U_3O_8.

Exploration is continuing in the area. A number of companies have land holdings and further discoveries have already been made, such as Tasman Resources and Rio Tinto's joint venture Vulcan prospect, where mineralization at low-grade but similar in style to Olympic Dam has been intersected in PACE-assisted boreholes at depths exceeding 850 m.

A similar IOCG deposit, Ernest Henry, named after an early prospector, was discovered near Mt Isa in 1993 during a contentious joint venture between WMC, Hunter Resources and Savage Exploration (a junior company). Savage had pegged a claim for iron ore in 1974 following a government aeromagnetic survey. They did little with it, and in 1989 WMC, who were looking for base metals, selected areas for detailed search. These included ground owned by Hunter Resources with whom WMC joint ventured as operator. WMC carried out a geophysical survey in 1990 which crossed into Savage's land, though no survey pegs were visible to mark it. WMC approached Savage in March 1991 for an option over various leases, including the area surveyed the year before. This was agreed in October 1991. Later that month the first drillhole put down by WMC intersected a major, intrusive, breccia-hosted, copper-gold deposit of Middle Proterozoic age on Savage's ground. Savage claimed that WMC had prior knowledge that the area was interesting. WMC conceded that errors had occurred and paid substantial damages (Metal Bulletin, 29 July 1993). It later sold its interest to Mt Isa Mines who developed the deposit. Ernest Henry originally contained 127 Mt at 1.14% Cu and 0.55 g/t Au, and was developed as an open-pit mine. Xstrata, who took over Mt Isa Mines in 2003, are converting the mine to a large underground sub-level caving operation to extend its life to 2024 with annual production of 50,000 t Cu.

A number of significant discoveries of copper-gold, Permian, sub-volcanic, breccia-hosted deposits have been made in northeastern Queensland near Charters Towers since the 1970s. The largest are Mount Leyshon and Kidston, both with resources of around 2-3M oz gold. The area was well known for small, low-grade gold deposits that had been worked since the 1870s with mines stopping at the water table (Teale and Lyons, 2004).

The WMC copper exploration initiative that discovered Olympic Dam also located the significant Nifty copper deposit in the Neoproterozoic Paterson Province of northern WA (near the Telfer copper-gold deposit) in the mid-1970s. This is a sediment-hosted, structurally controlled copper deposit with total resources of at least 60 Mt at a grade of 2.3% copper (Roach, 2010). It is now owned by the Indian company Aditya Birla Minerals and has an annual production of about 2 Mt of ore.

Cannington and Century

The Cannington orebody, discovered by BHP in 1990, is a major, mid-Proterozoic, sediment-hosted, silver-rich, lead-zinc deposit 250 km SSE of Mt Isa within the Diamantina Orogen. This orogen also hosts the Broken Hill ore deposit, and is thrust-faulted against the Carpentaria Orogen to the west which hosts the Mt Isa deposits. Cannington contained a pre-mining resource of 45 Mt at 11.1% Pb, 4.45% Zn and 500 g/t Ag and was commissioned in 1997 with full production by 1999. The underground mine is currently producing at a rate of 3 Mt/yr to be the world's largest producer of silver and lead with 6% and 7% of total world production respectively. Access is by a decline that is 5.25 km long and reaches to a depth of 600 m. The deposit is now owned by BHP Billiton and is a fly-in/fly-out operation. The trend towards this style developed in the 1980s to service small open-pit gold mines, thus avoiding the need to build a permanent township and to attract workers who would not live in an outback environment.

Century, discovered in 1990 by CRA Exploration, is a major, mid-Proterozoic, sediment-hosted, lead-zinc deposit 200 km NNW of Mount Isa, containing 105 Mt of ore at a grade of 12% Zn. The name refers to the 100 years between the first mining lease in the area and CRAE finding the deposit. It is now owned by Minmetals Resources of China. The area was known for minor lead veins in Cambrian carbonates but was not considered particularly prospective for stratiform deposits. The flat-lying, 45-m-thick orebody of laminated massive sphalerite and bituminous shale is contained within a mid-Proterozoic shale, siltstone and sandstone unit with a small and inconspicuous outcrop (Broadbent *et al.*, 1998). The ore contains almost no pyrite, so there was no conspicuous gossan to be noticed by earlier prospectors. Zinc soil anomalies were thought to be due to the minor lead veins until a sample of the discovery outcrop was analysed. The deposit was originally thought to be Sedex-style, but the strong bituminous content has led some people to consider that it formed well after sedimentation in an oil trap situation where zinc-rich metalliferous fluids were ponded in an organic-rich anticlinal trap. There was a long period of negotiation with Native Title claimants before development commenced in 2000, at a current rate of 500,000 t Zn per year. The orebody extends to 1.4 km by 1.2 km, and the open-pit mine is scheduled to close in 2015 as no extensions to the ore have been found. Minmetals Resources plans to replace its production by exploiting the Dugald River orebody,

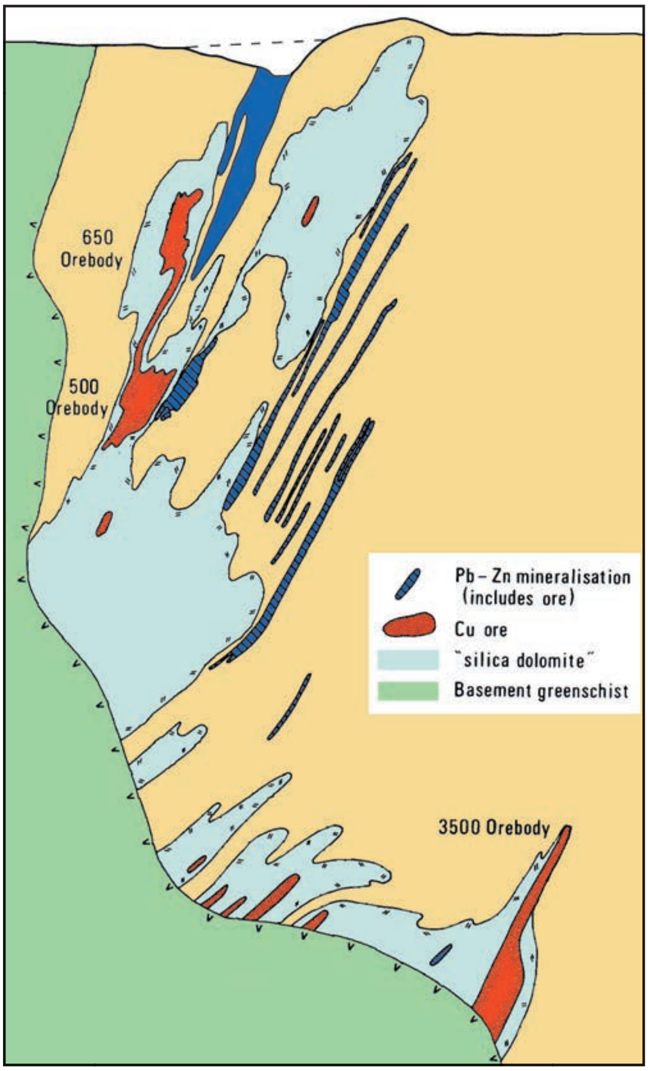


Figure 40. *Cross section, 1600m deep, through the series of orebodies at Mount Isa (after Perkins, 1990).*

another large Sedex-style lead/zinc deposit 100 km northeast of Mount Isa. This was discovered in 1881 and has been investigated by drilling intermittently since the late 1940s. It currently has resources of 48 Mt at 12.1% Zn, 2.1% Pb and 44 g/t Ag. The deposit is hosted in black shale and consists of a single lens over 2 km long and from 5 to 30 m wide which has been drilled to depths of at least 1000m. The mine life is estimated to be 23 years.

Mount Isa Mines continued to develop its adjacent lead-zinc and copper orebodies (Fig. 40). It was acquired by Xstrata in 2003 and currently annual output is about 6 Mt of copper ore from the Enterprise and X41 underground mines to produce 370,000 t Cu in concentrates and as anodes. Xstrata also extracts 8.6 Mt lead-zinc ore from the George Fisher underground mine and two open pit mines, to produce 355,000 t Zn in concentrates and 140,000 t of lead bullion with 6.8M oz Ag. The Enterprise mine reaches a depth of 1900 m making it Australia's deepest mine. In 2010 it had combined reserves and resources of 78 Mt at 3.3% Cu, and the X41 mine had 78 Mt at 2.1% Cu. The open-pit lead-zinc resources total over 100 Mt at a grade of about 7.5% Pb+Zn. The total pre-mining mineral endowment of the Mount Isa camp is around 400 Mt at grades of about 14 % Pb+Zn and 125 g/t Ag making it one of the world's largest base metal deposits (Huston *et al*., 2006).

More iron in the Pilbara

Exploitation of the Hamersley iron ore province has continued to develop and expand with the development of new ore bodies and new types of deposit. The already burgeoning iron ore output, boosted by demand from China, was further increased by the arrival of the Fortescue Metal Group (FMG) to join the original Rio Tinto and BHP companies. FMG developed a 24 Mt/yr mine at Cloud Break, a railway 250 km long and a new port at Port Hedland, all within just two years from 2006 to 2008. Their operations have already been expanded to 55 Mt/yr with a new mine at Christmas Creek, and there are plans for further increases and a new port near Dampier.

Figure 41*. Folded, sub-economic, banded iron formation exposed in the Hamersley Gorge.*

A 'Midwest' province of iron ore operations in WA is mining enriched portions of Archean banded iron formations east and southeast of the port of Geraldton. The first was by BHP in the 1960s at Koolyanobbing mine, north of Southern Cross, to supply its Kwinana steel works near Perth. This deposit is now mined by Cliffs Resources who export 8 Mt of direct shipping ore annually through the port of Esperance 600 km southeast of the mine. Other operations now export from the Jack Hills, Koolanooka, Extension Hill, Tallering Peak, and Karara, while a number of other deposits are under active exploration.

Annual Australian output of iron ore was 394 Mt in 2009, with the majority derived from the Hamersley Province (Fig. 17). This is 17% of world output and is backed by 34.5 Gt of Economic Demonstrated Resources, of which 80% are in the Pilbara Region and most of the rest is in other areas of Western Australia (Geoscience Australia, 2012).

The origins of the deposits have been investigated, and it is now thought that there were two major ore-forming periods in the Proterozoic and the Mesozoic (Kneeshaw *et al*., 2003). The older deposits generally have no relationship to present day topography, whereas the later ones have a strong correlation with it. Both formed by prolonged processes of supergene enrichment from the original 35% Fe to economic levels of over 60% Fe. Each period was accompanied by the development of irregular detrital deposits derived from the major bedded deposits. During Tertiary times additional detrital ores were deposited in drainage channels as long sinuous bodies, and many deposits of the various bedded, detrital and channel ores are now known. The original concept, of a broad basin with excellent lateral continuity of thin and thick beds over hundreds of kilometers in a low-energy chemical sediment environment, was challenged in the 1990s when high-energy carbonate and volcaniclastic turbidite beds attributed to volcanic eruptions and bolide impacts began to be recognized at a number of horizons through much of the sequence.

Gold again

A new copper-gold province has been developed since the 1980s west of Bathurst, NSW, based on the discovery of large-tonnage, low-grade, porphyry-copper deposits, similar to those mined in the Andes, but not previously recognized in Australia. The Northparkes deposit, near Parkes, was discovered by GeoPeko in 1982 in Ordovician andesitic volcanics and quartz monzonite porphyry intrusions. It is now operated by Rio Tinto, and comprises a number of ore bodies of disseminated chalcopyrite in quartz stockworks. An open-pit mine opened in 1992, followed by a series of block-caving underground mines in 1996, which operate at 5 Mt/yr at a grade of about 0.6% Cu. It currently has total reserves and resources of 440 Mt at 0.6% Cu and 0.3 g/t Au. Further exploration, including 140 km of drilling, is planned to extend the life of the mine beyond 2024.

Cadia Hill is a similar but larger deposit near Orange, and was discovered by Newcrest in 1992. Its open-pit mine is currently operating at around 16 Mt/yr at a grade of 0.6% Cu, while the underground block-caving Cadia, Ridgeway and Ridgeway Deeps deposit produces about 5 Mt/yr at the same grade. An even larger deposit has been discovered at Cadia East with total resources of 2300 Mt at 0.28% Cu and 0.44 g/t Au. This is planned to be a panel-cave mine operating at 16 Mt/yr with a life in excess of 30 years and will be the largest underground mine in Australia.

The Cowal mine, near West Wyalong and operated by Barrick in a major, porphyry-style gold deposit within Ordovician volcaniclastic and intrusive rocks, produced 298,000 ounces of gold in 2010. Reserves were stated by Barrick in 2010 at over 129 Mt containing 3.5M oz Au, with a mine life of at least 15 years.

Further exploration to the south, along the trend of the Lachlan Fold Belt, is revealing additional deposits of the porphyry class, including Dart Mining's Unicorn molybdenum-copper deposit near Corryong in northeastern Victoria which Dart claims has similarities to the major Henderson molybdenum deposit in Colorado. Current resources announced by Dart total over 100 Mt at 0.039% Mo, 0.057% Cu and 3.1 g/t Ag.

The old Victorian gold field, which had been moribund since the 1920s, was investigated from the late 1970s by WMC. They targeted the Bendigo field (Fig. 42), as this had been the most productive area with 22M oz from 11 parallel lines of anticlinal 'saddles' of quartz reef worked to around 750 m depth. The underlying idea was that the saddles carried on below this depth and that modern mining, pumping and processing techniques could recover large amounts of gold economically. WMC spent 15 years gathering data on over 2000 companies, modeled over 300 shafts and put down 45 km of drill holes without establishing sufficient mineable resources. This research was carried on by Bendigo Mining, which floated specifically to develop the Bendigo field. The company spent $105 million over 8 years drilling 110 km of boreholes, driving the Swan decline 5.5 km to a depth of 850 m to access one of the anticlinal lines, and analyzing a hundred 100-t bulk samples and 30,000 t of development samples. They estimated that 11M oz of gold should be present between 750 m and 1500 m depth with an average grade of at least 9 g/t, and they planned to recover at least 200,000 ounces of gold per year. However, when mining began in 2006 the results did not live up to expectations. The average grade for 130,000 t mined in six months was only 5.5 g/t at a total cost of $600 per ounce when the gold price was between $550 and $700. The nugget-rich nature of the gold-bearing mineralization caused severe problems in reconciling the grade estimated from drilling and trial mining to that actually achieved during production. Bendigo changed its name to Unity Mining in 2010 and is now operating at about 25,000 oz per year. The nearby Ballarat and Fosterville gold fields have also had a renaissance, and are currently in production by AuRiCo Gold at a rate of 100,000 oz/yr.

***Figure 42**. The farmlands of Victoria, where gold was once worked and new reserves are being found.*

Exploration in the fertile Mount Read Volcanics on Tasmania's west coast continued to discover new orebodies. The small Que River (3.3 Mt) and medium-sized Hellyer (16.5 Mt) high-grade copper-lead-zinc-silver-gold VMS deposits were found by Aberfoyle in the 1970s and 80s and are now worked out. The small but high-grade Henty orogenic lode gold deposit (2.8 Mt at 12.3 g/t Au), found by Renison Goldfields Consolidated in the 1980s, has already produced 1.2M ounces since production began in 1996. It is now owned by Unity Mining who are making additional discoveries.

Heavy mineral sands

A major new heavy mineral sand province was discovered by CRA in 1981 near the town of Horsham in southeastern Victoria. It occurs in Tertiary sands on the eastern edge of the Murray Basin, which occupies around 300,000 km^2 in southeastern Australia. Unlike the eastern and western coastal deposits, this was not a strand-line fossil beach deposit but is thought to be formed in an offshore basin during storms that resulted in the sorting of the various mineral fractions. The deposits occur in long, thin lenses. The province was found during regional exploration for a variety of targets, including gold in the pre-Tertiary basement and gold, uranium and heavy minerals in the Tertiary basin sediments (Williams, 1990). The deposits are unusual in being rich in rutile and zircon, rather than ilmenite, and the minerals are very-fine-grained, making them more difficult to separate than the coarser coastal deposits. The CRA leases were taken over by Iluka, and production started from the Douglas deposit in 2004; it currently achieves annual rates of 75,000 t of rutile and 70,000 t of zircon. Initial resource estimates were 4900 Mt at a grade of 2.8 % heavy minerals, but Iluka's current Murray Basin reserves and resources total around 300 Mt at grades of 12-24% total heavy minerals, of which about 50% are ilmenite, 15% rutile and 12% zircon.

Project	State	Output	Company
Kunwarara	Qld	100,000	Australian Magnesium Corp.
Main Creek	Tas	80,000	Pacific Magnesium Corp.
Arthur River	Tas	190,000	Crest Magnesium
Woodsreef	NSW	80,000	Pacific Magnesium Corp.
Leigh Creek	SA	50,000	South Australian Magnesium Project
Batchelor	NT	10,000	Mount Grace Mining
Latrobe	Vic	100,000	Latrobe Magnesium
Murrin Murrin	WA	NA	Anaconda Nickel

***Table 2**. Projects for producing magnesium, with outputs as annual tonnage, as proposed in 2001 (after Sandford, 2001).*

A number of other companies are currently exploring in the Murray Basin. Iluka has also discovered a similar but zircon-rich province (50% of the heavy minerals are zircon) along ancient shore lines of the adjacent Eucla Basin, also in Tertiary sediments, on the edge of the Nullarbor Plain. Total reserves are about 350 Mt at 4-6% heavy minerals made up of 50% zircon, 28% ilmenite and 5% rutile. The Jacinth-Ambrosia deposit came into full production in 2010 at a rate of 300,000 t/yr of zircon, which is about 25% of current world consumption. The ancient mineralized shoreline stretches over 1200 km from South Australia into Western Australia. Diatreme Resources recently announced a positive feasibility study for their Cyclone deposit, located in WA 25 km west of the SA border. Their project has the potential to mine ore at 10 Mt/yr for 10 years.

There was considerable interest at the turn of the century in the possibilities of major magnesium metal production from Australia in conjunction with developments in the automotive industry. A number of major projects were proposed (Table 2); all were based on mining magnesite except for extraction from chrysotile tailings at Woodsreef and from brown coal fly-ash at Latrobe.

None of these projects progressed beyond the feasibility stage, apart from Kunwarra which was abandoned in 2003 when only 5% complete. All were unable to raise the necessary finance, as their prospective automotive partners would not commit to buying magnesium until the metal was being produced.

Government support

The mining industry has been considerably assisted for many years by various research arms of the national and state governments. The national Bureau of Mineral Resources was established in 1946 and carried out a large number of small and large surveys in most parts of Australia. Initially focused on uranium exploration, it developed expertise in airborne magnetic and radiometric surveys which proved hugely useful during the nickel boom when the aeromagnetic map was frequently the only source of geological information for the prospector looking for slightly magnetic basic and ultrabasic volcanic rocks which might host nickel deposits. It was subsumed into the Australian Geological Survey Organisation when that body was formed in 1992, and then became Geoscience Australia in 2001. The Commonwealth Scientific and Industrial Research Organisation (CSIRO) also carries out widespread research in geological, mineralogical, environmental and other issues of relevance to the minerals industry.

Each Australian state maintain some form of Geological Survey and Mines Department that carry out geological mapping, manage mineral licences and leases and maintain historical records of production data, drill cores and exploration information. From time to time they have also encouraged exploration with various forms of incentives, including paying for speculative drilling, carrying out targeted mapping programmes and creating promotional literature. These schemes can be found on the various state websites that are listed in the references. They also have increasing amounts of on-line data, maps and other resources, much of which can be freely downloaded.

The future

A large number of significant discoveries and developments have been made in Australia in the past 170 years, and the country is now a major producer and exporter of a wide range of mineral commodities. All of these discoveries, with the exception of Olympic Dam, Prominent Hill, Carapateena, Abra, and Admiral Bay, were located in exposed host rocks. There are substantial reserves and resources remaining around the existing deposits, and new deposits will be found in the vicinity but these will be largely exhausted over the next few decades. Many of the major deposits, such as Kalgoorlie, Mount Isa and Olympic Dam, occur adjacent to major, deep-rooted crustal lineaments or dislocations that focused the flow of mineralising fluids to enable the deposition of minerals in suitable host rocks and environmental conditions. Future exploration will have to develop methods of locating and investigating suitable host rocks and structural situations under increasing depths of barren cover. These methods will include more powerful and discriminatory seismic, magnetic and electromagnetic techniques, as well as more sophisticated geochemical methods to detect leakages of elements from concealed orebodies. Exploration over the past forty years has varied in intensity and target commodity, but expenditure is now approaching Aus$2500M annually (Fig. 43).

A recent trend has been the rapid acceleration in the depletion of ore deposits, exemplified by the working out of the major Century deposit in just 16 years between 2000 and 2015. This growing trend increases the urgency for the need to discover more major deposits capable of being worked economically at high rates.

Australia will continue to be a major producer and exporter of a wide variety of minerals and metals. It currently does not produce significant quantities of

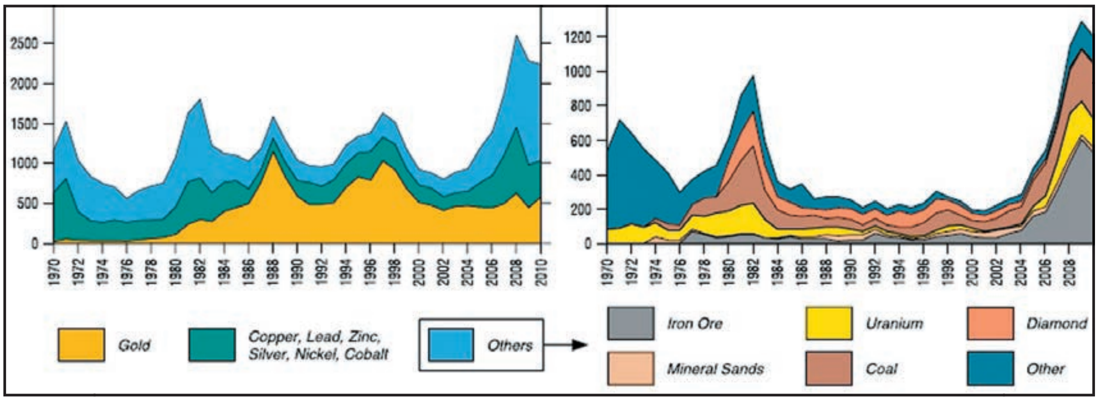


***Figure 43**. Annual expenditure, in M A$, on mineral exploration in Australia between 1970 and 2011 (after Senior and Huleatt, 2012).*

potash, baryte, chromite, platinum group elements, rare earth elements, fluorspar, tin, tungsten, molybdenum and phosphate. However, there are known deposits with large resources of most of these minerals.

The Mount Weld deposit in WA is a world-class resource of rare earths, and initial mining commenced in mid-2008 with the ore currently stockpiled; processing is expected to commence soon. Newmont's recently discovered O'Callaghan deposit near its Telfer gold mine is a major, sub-horizontal, tungsten skarn deposit at a depth of 350 m below surface at the contact of granite and overlying limestone. It has probable reserves of 57 Mt at 0.34% WO_3 and indicated resources of 69 Mt at 0.34% WO_3 (Geoscience Australia, 2012). Moly Mines Molyhill deposit (formerly Spinifex Ridge) in the Pilbara is a world-class molybdenum resource with 650 Mt at 0.05% Mo, 0.08% Cu and 1.8 g/t Ag. There are several major titanium-vanadium prospects in WA of which the Barrambie deposit near Meekatharra with resources of 100 Mt at 0.82% V_2O_5 and the Speewah deposit in the Kimberleys with resources of 3600 Mt at 0.30% V_2O_5 and 2% Ti are the largest. The Cambrian-hosted Phosphate Hill deposit near Mt Isa, with large resources of 32% P_2O_5, has been worked sporadically since its discovery in 1966. It is now owned by Incitec Pivot Fertilisers who have recently developed an open-pit mine with a capacity of 900,000 t/yr to manufacture fertilisers using sulphuric acid from the Mount Isa smelter. There are also numerous promising platinum deposits, including the Munni Munni deposit near Karratha in the Pilbara; its resource of 24 Mt at 2.9 g/t Platinum Group Metals, in a large layered intrusion dated at 2920 Ma, was established by Hunter Resources in the 1980s. The deposit is now owned by Platina Resources, but no production has taken place.

***Figure 44**. The Australian Outback, where mineral orebodies still await discovery.*

The mining industry can have environmental problems. It is a major user of water, and conflicts have occurred over water use in agricultural areas, such as in the Orange and Cadia areas of New South Wales during periods of drought. Some trends can be anticipated, and there will continue to be increasing foreign ownership of Australian resources, particularly with the upsurge in Asian investment in the mining sector. It will continue to be a highly regarded country for mineral exploration and exploitation, though the recent hotly-debated federal Mineral Resource Rent Tax on profits from iron ore and coal, and the newly introduced Carbon Tax, are causing major mining companies to reconsider some of their future investment decisions. But however situations develop, Australia is sure to continue to be a major supplier of the world's minerals.

Acknowledgements

Dr Gavin Mudd of Monash University Melbourne is thanked for access to his historic production statistics of Australian mining, from which production graphs have been made. Images have been kindly provided by Rio Tinto, KGMA and Copper Mines of Tasmania. The abundance of material on many company and national and state geological survey websites has been of substantial assistance. The author also thanks Prof Geoffrey Blainey whose book *The Peaks of Lyell* sparked his interest in Australian mining and its history. Two reviewers are thanked for comments that substantially improved the text.

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crcleme.org.au/RegExpOre/Poona.pdf
dartmining.com.au/
environment.gov.au/ssd/supervision/arr-mines/index
excaliburmining.com.au/IRM/content/project_tennant
goldroad.com.au/projects-yamarna.php
iluka.com/murraybasin/index
lynascorp.com/index.asp
mining-technology.com/projects/george_fisher/
mining-technology.com/projects/mount_isa_copper/
newcrest.com.au//index.asp
northparkes.com.au/index.aspx
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perilya.com.au/
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NT: nt.gov.au/d/Minerals_Energy/Geoscience/
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SA: minerals.pir.sa.gov.au/geology
Tasmania: mrt.tas.gov.au/
Victoria: dpi.vic.gov.au/earth-resources
WA: dmp.wa.gov.au
Commonwealth (CSIRO): csiro.au/

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Thixotropic wedges or fluidised water-escape columns in the Charnian Supergroup at Bradgate Park

John N. Carney

Abstract: Discrete, funnel-shaped structures consisting of downwarped and disrupted strata are described from a restricted stratigraphical interval in the Late Neoproterozoic Charnian Supergroup, just above the base of the Bradgate Formation at exposures in Bradgate Park, in Charnwood Forest, Leicestershire. The structures occur within a deep-water marine turbidite succession and have attracted much attention, with a variety of explanations advanced to account for their origin including volcanic bomb-impacts and burrowing organisms. This article describes these structures, interprets their mode of origin, and concludes that they compare with features known as ‘thixotropic wedges’. The latter have been described from various other parts of the world and are commonly placed within a category of soft-sediment deformation phenomenon known as ‘seismites’. Such an association may have important implications for the style of turbidite sedimentation in the Charnian Supergroup as a whole.

In south-eastern Charnwood Forest, Bradgate Park exposes the younger formations of the Charnian Supergroup (Moseley and Ford, 1985), which is of latest Neoproterozoic (Ediacaran) age (Fig. 1). With respect to conditions of sedimentation and palaeoenvironments, one particularly interesting part of this sequence occurs within the Maplewell Group at the transition from the Beacon Hill Formation into the overlying Bradgate Formation. The latter’s base is delineated by a horizon of disturbed bedding that includes the Sliding Stone Slump Breccia Member, the type locality (SK 5304 1133) for which was designated by Moseley and Ford (1985) as the partially wooded crags immediately west of the Sliding Stone enclosure (Fig. 1).

Narrow zones of strongly downwarped bedding and lamination occur in strata capping the Sliding Stone Breccia at its type locality. These structures have been a source of debate among visitors to the park for many years, but they are comparable with an unusual type of soft-sediment deformation phenomenon that has been described from a variety of sedimentary environments in other parts of the world.

Local geological setting

The downwarped strata are exposed immediately below a south-easterly dipping bedding plane at the eastern limit of the Sliding Stone Slump Breccia Member type locality (Fig. 1). The member is a prominent unit that forms an important stratigraphical marker bed throughout the outcrop of the Charnian Supergroup. However, it may also be considered as the upper and most readily mappable component of a more extensive interval of slumped and incipiently disrupted bedding which encompasses strata estimated to be about 100 m thick in the Out Woods, 5.5 km farther north (Carney, 1994). In Bradgate Park, this broader zone of disrupted bedding comprises the exposures around Old John Tower, and can be extended farther east to include the ‘Park Breccia’ of Moseley and Ford (1985) (Fig. 1).

In sedimentological terms as well as in age, the strata containing the downwarped structures clearly post-date the Sliding Stone Slump Breccia. The latter does, however, provide important evidence for the style of sedimentation prevailing at around that time. It commences (Fig. 2) in thick, structureless, coarse-

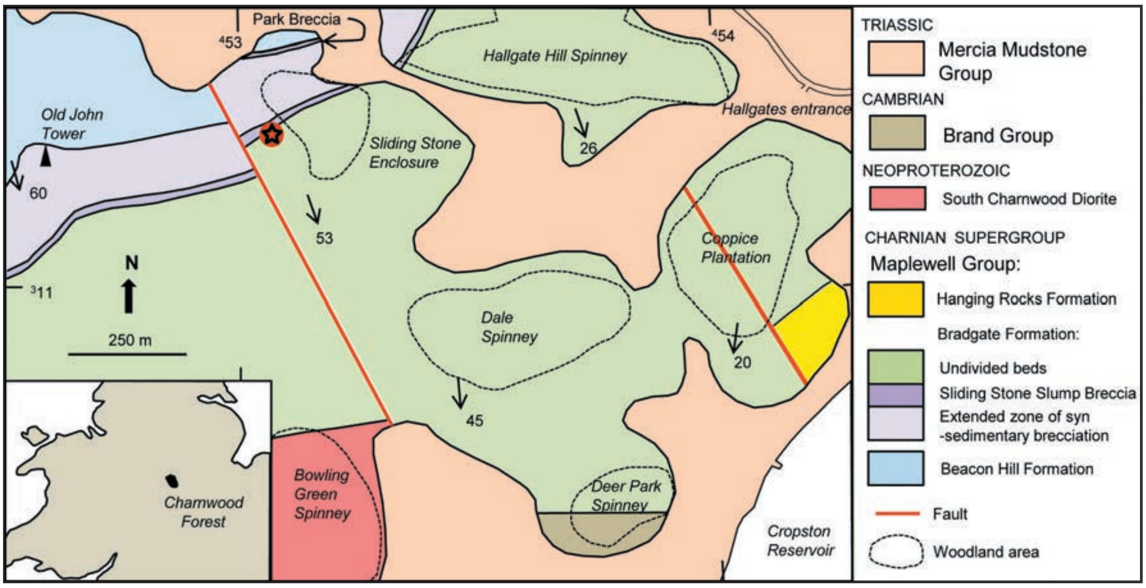


***Figure 1**. Geology of eastern Bradgate Park, with a black and red star at the location of the downwarped structures (modified from BGS 1:10,000 sheet SK51SW).*

to granule-grade volcaniclastic sandstone containing abundant angular fragments and larger contorted rafts of laminated mudstone. This passes up into progressively finer grained and better sorted sandstone in which bedding and lamination become increasingly well developed. The basal facies with abundant mudstone inclusions is distinctive, and, for lithologies such as this, two alternative explanations are considered by Ogiwara and Ito (2011). They may be the deposits of a slope-collapse event (submarine landslide) that generated the *en masse* flowage of granular material containing debris of disaggregated, partially consolidated strata (the sediment rafts). Alternatively, they may represent variably consolidated strata disaggregated by in situ diapiric sedimentary injection.

The former explanation for the Sliding Stone Slump Breccia Member was favoured by Moseley and Ford (1985; 1989) and is endorsed here for two reasons. First, the unit's tabular form and its widespread distribution along a constant stratigraphical horizon throughout the Charnian Supergroup preclude a localised diapiric origin. Secondly, the changes noted above within the upper part of the unit (i.e. overlying the structureless sandstone with mudstone fragments) suggest the incoming of traction sedimentation combined with progressively waning current flow, which is typical of the 'Bouma' cycles seen in strata deposited from turbidity currents (Bouma, 1962). To account for the lower part of the member, however, a refinement of the Bouma model proposed by Shanmugam (1997) may be applicable. Thus the structureless sandstone with mudstone fragments is interpreted as a debris flow which, upon transformation into a normally graded turbidite, would give the vertical changes shown in Figure 2. This interpretation, combined with the exclusively volcanogenic nature of the grain constituents, is in keeping with the suggestion that the Charnian Supergroup accumulated either on or at the base of a submarine slope that flanked a moderately deep to deep-water turbidite basin marginal to an active volcanic arc (*e.g.* Moseley and Ford, 1985, 1989; Carney, 1999).

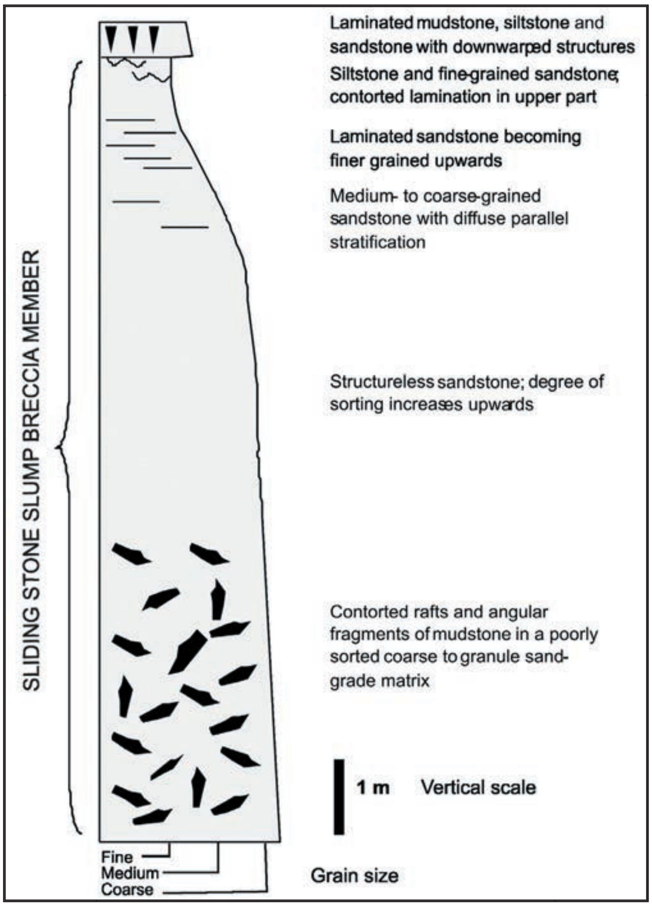


***Figure 2**. Measured section in volcaniclastic strata of the Sliding Stone Slump Breccia Member at its type locality, including the overlying beds with downwarped structures.*

Description of the structures

The term 'downwarped structure' is used here in a non-genetic sense, to describe discrete, funnel-like features that form part of an otherwise relatively undeformed sequence of thinly bedded to laminated volcaniclastic mudstone, siltstone and fine-grained sandstone immediately overlying the Sliding Stone Slump Breccia Member (Fig. 2). At the locality shown in Figure 1 three such structures, spaced between 1 and 2 metres apart, all occur above the same stratigraphical horizon, which is defined by a sandstone layer about 20 mm thick

The middle of the three structures, being the better developed, forms the basis for the present description. It extends for 18 centimetres vertically, between lower and upper planar undisturbed bedding surfaces that respectively delineate the commencement and cessation of the disturbance (Fig. 3a). The structure opens upwards to a width of about 9 cm and has a slightly arcuate axis. A marked asymmetry is imparted by a) the steeper downwards curvature of strata on the right-hand (south-east) side of the structure compared to those on its left-hand side, b) the observation that strata on the right-hand side appear to be displaced upwards, compared to those on the left of the structure (Fig. 3b), and c) the steep, south-eastwards tilt of the axis of the structure (after restoration for the local tectonic dip). The left-hand margin of the structure is in part defined by syn-sedimentary microfaults with listric displacement into the axis of the structure. By contrast, its right-hand margin, although similarly microfaulted, is principally delimited by the steep downwards curvature of strata, noted above, and by the pinching out of some laminae; lower down this margin becomes serrated and ill-defined, with syn-sedimentary microfaulting present (Fig. 3b).

The upper part of the structure is defined by three sets of mudstone/siltstone laminae which show a downwards trend of increasing deformation. The highest such package, coded blue in Fig. 3b, shows only slight draw-down and no obvious thickening in the centre of the structure, although it does thin slightly where it crosses the left-hand margin. Beneath this, the green-

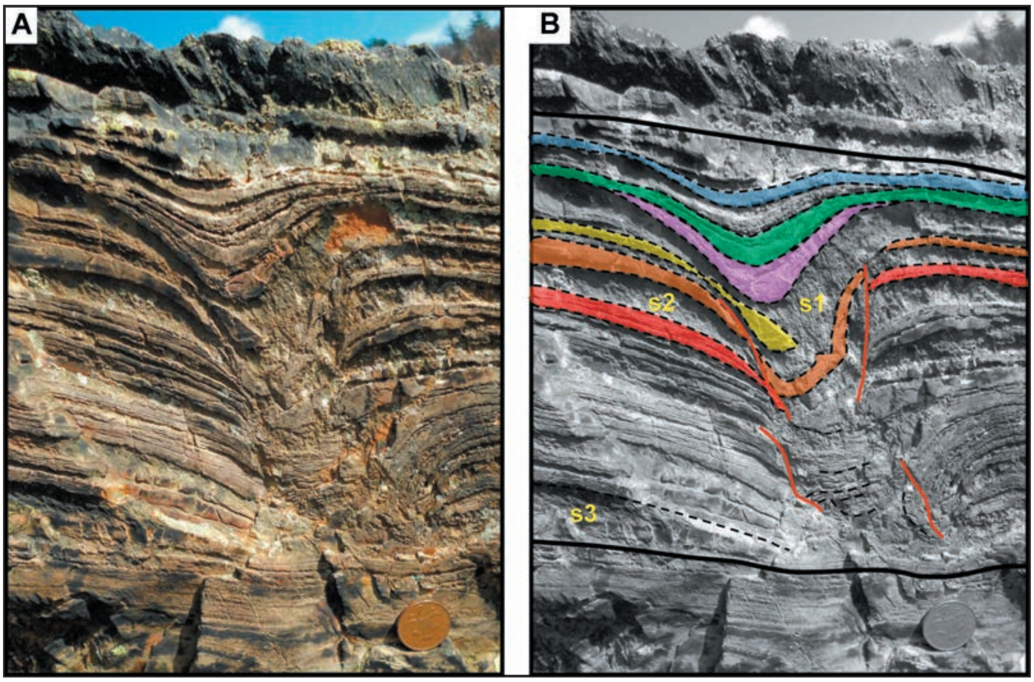


***Figure 3**. Analysis of the Bradgate Park structures. **A**: Close-up of a downwarped structure; the camera was rotated so that the strata appear in their inferred original near-horizontal attitude; the coin is 2.5 cm in diameter. **B**: Analysis of the structure shown in A; thick black lines are upper and lower bounding surfaces of the disturbed zone; black dashed lines highlight selected crumpled laminae in lower part of the structure; thin red lines are the principal syn-sedimentary microfaults; post-depositional microfaults are not highlighted; 's1-3' are prominent volcaniclastic sandstone layers. See text for explanation of other features.*

coded laminae show a greater degree of draw-down and thickening, while remaining unbroken when traced outwards into the adjacent undisturbed sequences. The laminae coloured pink in Fig. 3b thicken significantly and are drawn down into the axis of the structure, pinching out across its margins.

Mudstone strata in the lower part of the structure show the most significant disruption (Fig. 3b). A yellow-coded set becomes attenuated before disappearing in the axis of the structure. Beneath it, the brown-coded lamina becomes highly attenuated and disrupted across the left-hand margin of the structure, where it is also displaced by a syn-sedimentary microfault; on the right-hand side it becomes severely up-turned and stretched to breaking point as it crosses that margin of the structure. The lowest lamina (coded in red on Fig. 3b) that can be traced with reasonable confidence loses its identity in the central part of the structure, as do all of the strata beneath it. Here, the axial zone of the structure features crumpled, down-flexured laminae and microfaults.

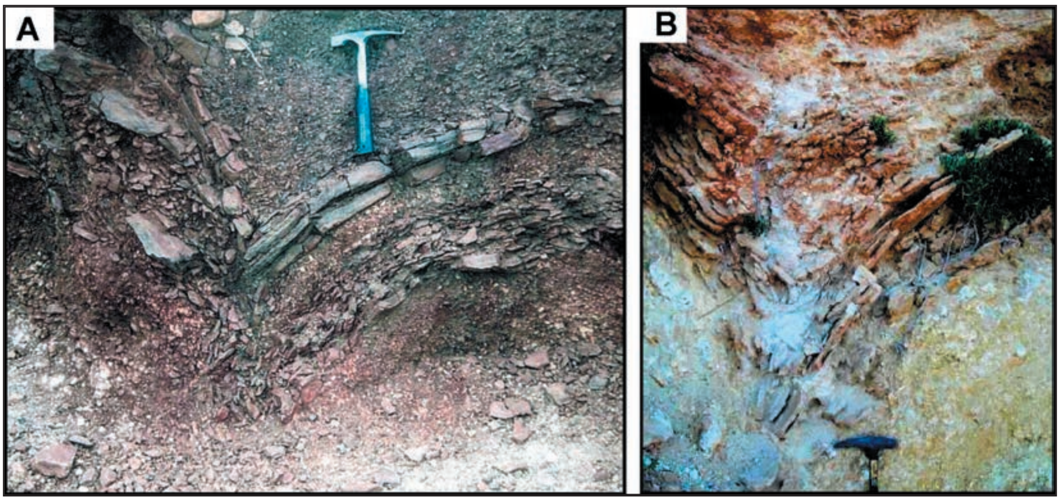
Three particularly prominent sandstone beds (s1-3, Fig. 3b) show marked thickness variations with respect to the axis of the downwarped structure. The upper sandstone (s1) thickens into the axis, where it appears to engulf the termination of the yellow-coded mudstone lamina. A lower sandstone (s2) thins towards and terminates against the faulted left-hand margin of the structure, as does the basal sandstone (s3). The latter can be traced across the exposure and forms the horizon into which all three downwarped structures are considered to 'root'. It should be noted that there are many other thinner sandstone laminae; they can be distinguished on Fig. 3a by the fact that they weather-in, relative to the mudstone and siltstone beds which stand out on the surface of this exposure.

Interpretation

Previous explanations for these structures were reviewed by Carney (2010), and include: volcanic bomb-impacts, burrows, and disturbances produced by the escape of trapped water or gases. The 'bomb-impact' suggestion is implausible given the absence of large volcanic fragments in this part of the succession, and also the fact that reconstructions after folding show that this locality must have lain about 14 kilometres from the contemporary volcanic centres located in the north-western part of the Charnian Supergroup outcrop (*e.g.* Carney, 1999). An organic explanation is also dismissed; not only are these structures (Fig. 3a) atypical of burrows, but deeply-penetrating burrows on this scale are unknown in Neoproterozoic rocks where the Ediacara macrobiota, which is well represented in Bradgate Park (Boynton and Ford, 1995), consists of surface impressions and trails only.

A further comparison, with syn-sedimentary load structures of the type observed elsewhere in Bradgate Park (*e.g.* Ambrose *et al*., 2007, p.25), can also be ruled out. Load structures typically result from reverse density/porosity contrasts between adjacent beds or laminae causing, for example, the formation of a 'Rayleigh-Taylor perturbation' (Visher and Cunningham, 1981). This commonly results in the downwards penetration of sandstone as lobe-like masses into an adjacent underlying mudstone. By contrast, Fig. 3a shows that the downwarped structure is considerably more complex than this, affecting numerous sedimentary layers with a variety of physical properties ranging from mudstone through to siltstone and fine-grained volcaniclastic sandstone. There are, however, two further, interrelated categories of soft-sediment deformation that can be considered.

*Figure 4. Comparisons with thixotropic wedges. **A**: Structure compared to a thixotropic wedge and attributed to syn-sedimentary seismicity within argillites of the Mesoproterozoic Lokapur Subgroup in southern India (photo: S. Patil Pillai). **B**: Thixotropic wedge in Pliocene marls of the Trubi Formation, south-eastern Sicily, attributed to nearby seismicity (after Pirrotta and Barbano, 2011).*



Thixotropic wedges

'Thixotropic wedges' are narrow, discrete funnel-like structures featuring laminae that show draw-down and disruption (*e.g.* Montenat *et al*., 2007) as a result of complex processes associated with sediment mobilisation (see below). They can occur over a range of environments and ages, and two examples are shown for comparison in Figures 4a and b. The former is from thinly interbedded shales and siltstones of Mesoproterozoic age, inferred to have accumulated as mudflats in a shallow water environment (Patil Pillai and Kale, 2011). The second example (Fig. 4b) is from a Pliocene, carbonate-dominated sedimentary sequence deposited in moderately deep waters (Pirrotta and Barbano, 2011). This latter example most resembles the Bradgate Park structure: it has a well-defined lower, chaotic infill, which includes downwarped, detached remnants of laminae, and an upper zone in which sedimentary layers show progressively less deformation, but nevertheless exhibit draw-down across the axis of the involution.

Sediments containing water are able to deform like this if they exhibit thixotropy, which is defined as the property of materials that are stable when at rest under normal conditions, but which then become liquefied and are capable of flowage when shaken, agitated, or otherwise stressed in the absence of any introduced fluid (*e.g.* Boswell, 1951; see also the review by Barnes, 1997). Gels and colloids are thixotropic materials that exhibit these properties; however, Boswell (1949) stated that all sediments, barring clean (i.e. mud-free) sands, can behave similarly under appropriate conditions, with clays showing the strongest properties in this respect. The experiments conducted by Boswell (1951) found that shaking was a particularly effective mechanism for bringing about the virtually instantaneous mobilisation of thixotropic sediments. Moreover, shaking is directly applicable to geological situations and is the favoured triggering mechanism for settings in which water-saturated, thixotropic sediments are suggested to have been mobilised by seismic activity (*e.g.* Montenat *et al*., 2007).

Where thixotropic sediments become mobilised, liquefaction occurs in an essentially closed system. The process is driven by the breakdown of the grain framework and transfer of grain support to the pore fluid, and could be caused by an increase in pore fluid pressure as a result of seismically-induced shaking (Ishihara, 1993; Owen, 1996). In a broader context, however, it is also possible that liquefied water/sediment mixes generated through shaking in one part of a thixotropic sediment column could migrate laterally into another part. In the latter areas, the injection of an extraneous water-sediment mix would result in the complementary process of fluidisation.

Fluidisation

The post-depositional escape of fluidised water-sediment mixes typically results in up-domed laminae of the type commonly found in the root zones of sand volcanoes (*e.g.* Montenat *et al*., 2007). The fluidisation experiments of Frey *et al*. (2009), however, are more relevant to the features under discussion here, because they show that under certain conditions laminae can also be drawn downwards. In one experiment (Frey *et al*., 2009), water was initially injected upwards into the base of a static, sand-rich sedimentary sequence with thin intercalated silt layers (Fig. 5a). The added water resulted in pore expansion and eventual fluidisation of a column of sand, but as barriers to flow (the silt layers) were encountered the fluidised column turned and circulated downwards, producing a water-and-sediment convection cell. The force exerted by the convecting fluid first up-domed the overlying silt layer, and then breached it, causing draw-down of adjacent laminae into the zone of fluid injection (Fig. 5b). This process was repeated as the cell migrated upwards, through successive silt-barriers, resulting in a funnel-shaped column with a width of approximately 3 cm composed of homogeneous sand. The adjacent silty layers arched downward toward the margins of the column, and terminated abruptly at its walls, which were relatively straight and vertical (Fig. 5c). Frey *et al*. (2009) noted that although sand volcanoes were commonly produced at the surface of the injection column, most of the fluidised sand was retained within it.

The Bradgate Park structures (Figs. 3a, b) show some similarities to those produced experimentally by Frey *et al*. (2009); for example, the thinning-out of some sandstone layers (s1, s3) towards the downwarped structure and complementary draw-down of overlying mudstone and siltstone beds and laminae. Although the model of Frey *et al*. (2009) does feature layered sediments, it is sand-dominated and thus not strictly comparable to the varied mud/silt/sand sequence seen at Bradgate Park. In this more complex lithological situation, where there are rapid alternations between relatively thin sand and mud/silt layers (Fig. 3a), it is unlikely that the processes modelled by Frey *et al*. could operate efficiently unless other factors were involved.

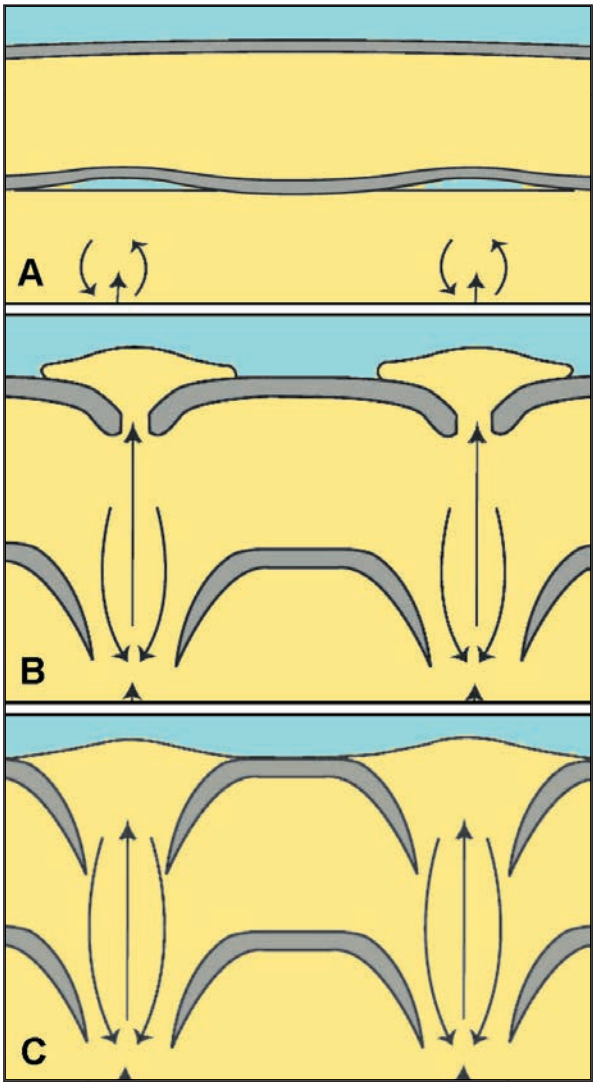


Figure 5*. Sequence of events during water-escape experiments in sediments composed of sand and silt - the shaded layers (after Frey et al., 2009).* ***A****: Initial fluidization due to upwards injection of water into lower layers; water collects in void beneath up-domed silt layer.* ***B****: Continued fluidization results in a water/sediment convection cell, causing the progressive draw-down of silt layers.* ***C****: Stable column of circulating sediment and water established for as long as fluid injection process was continued.*

One possible supplementary mechanism is suggested by Thorsson *et al*. (1986), from studies of Late Quaternary clays, silts, sands and gravels showing wedge-shaped zones of downwarped strata. In the 3-D outcrops available for that study, those structures correspond to tensional fissures inferred to have opened during seismically induced shaking. It was suggested that the fissures allowed mobilised sand from underlying overpressured strata to be injected upwards as fluidised columns. This process caused the mobilised sand layers to thin towards the fissures, and overlying silty strata to collapse into them, resulting in microfaulting and downwarped laminae similar to the features highlighted in Figure 3b.

No fissuring could be identified in association with the Bradgate Park structures, for which only 2-D exposure was available (Fig. 3a); however, one other feature of the Thorsson *et al.* (1986) model that bears comparison is their description of an upper filled 'sediment plug' in which strongly downwarped beds thicken into the axis of the fluidised columns and pinch out along their margins. These geometrical relationships recall similarities to the upper pink, green and blue-coded laminae in Figure 3b, for which two explanations are possible. If these upper sediment layers constitute a post-deformational sedimentary infill, as in the Thorsson *et al*. examples, they may represent muddy or silty, distal turbidites that had sloughed into the still-open fissure and progressively filled it. Alternatively, they could represent part of the sedimentary sequence into which tensional fissuring had not propagated, but which nevertheless were drawn down above the disturbance, deforming plastically as they did so to produce the observed trend of thickening.

The absence of sand or silt volcano edifices in the Bradgate Park occurrences suggests that any fluidised sand drawn into the downwarped structures did not reach the surface but may have migrated laterally along it, perhaps to be vented upwards elsewhere.

Discussion

The Bradgate Park downwarped structures are suggested to most closely resemble the category of discrete, soft sediment deformation phenomenon that have been given the part-genetic, part-descriptive name of 'thixotropic wedge'. Such structures are unusual in the geological record, and are postulated to have resulted from the mobilisation of thixotropic sediments upon seismically induced shaking (*e.g.* Montenat et *al*., 2007). With this interpretation it can be suggested that soon after deposition parts of the Charnian sedimentary sequence were capable of being liquefied, to flow like fluids over a relatively short period of time before returning to a stable condition after the triggering movements ceased.

Features similar to thixotropic wedges were produced by the fluidisation experiments of Frey *et al*. (2009). Although such experiments were performed in the absence of shaking, the results (Figs. 5a-c) nevertheless imply that fluidisation may be a process complementary to liquefaction during the formation of thixotropic wedges. This linkage is likely to occur when water-saturated, thixotropic sediment becomes liquefied upon seismic shaking and is then injected into a separate part of the sediment column (*e.g.* Thorsson *et al*., 1986). Thus for the Bradgate Park structures a possible scenario is that overpressuring facilitated the lateral movement of mobilised sediment, which then was evacuated upwards as narrow, fluidised columns into tensional fissures formed during the same bout of seismicity. After upwards injection was largely completed, the more coherent silt or clay-rich laminae deformed plastically and collapsed into the fissures, resulting in the formation of complex, downwarped structures comparable to a 'thixotropic wedge'.

The observed asymmetry of the Bradgate Park structures suggests a superimposed component of compression, directed from right to left in Fig. 3a. If occurring towards the end of the seismic event, this may have been the mechanism that closed off the circulation of fluidised material, resulting in the cessation of collapse and downwarping. Late compression appears to be at odds with the tensional model proposed above; however, it could be compatible with a sideways seismic shaking motion within water-saturated sea-floor sediments transmitted by the action of P-waves, which change the volume of intervening material by alternating expansion and compression (Milsom, 2003).

Most authors refer thixotropic wedges to the spectrum of soft-sediment deformation phenomenon known as 'seismites' (Seilacher, 1969), which are triggered by earthquake-induced shaking of water-saturated sediments. Indeed, the scheme of Montenat *et al*. (2007; their fig. 3) goes as far as classifying thixotropic wedges within their category of 'seismites *sensu stricto'*, together with other features such as sand volcanoes and diapirs. It is thought that seismic shocks generate a recurrent horizontal shear strain effect in unconsolidated thixotropic deposits (Davidovici, 1985), causing an instantaneous segregation of the liquid from the solid sedimentary phase. According to Montenat *et al*. (2007), the sediments most susceptible to this type of deformation are fine-grained materials with contrasting granulometry, such as alternating beds of mud, silt and fine sand. In such sequences, which greatly resemble the example from Bradgate Park discussed here, the phenomenon is characterized by: (1) destruction of the sediment structures, (2) modification of pore-fluid pressure, (3) refitting of grains which leads to an increase in the density of the granular phase, and (4) overpressuring of a water-saturated sedimentary sequence, which is responsible for the phenomena of expulsion and/or injection of a liquefied phase (water+smallest grains and mud), generating the seismite structures. These phenomena have been modelled in numerous studies, with experiments and measurements reproducing different seismite structures (Kuenen, 1958; Owen, 1987).

A caveat to this is that 'seismite' is a strongly genetic term, relating more to a cause than to a diagnostic rock fabric or structure. It should therefore be applied with caution, particularly since phenomenon caused by fluidisation and fluid expulsion can occur independently of seismicity (see reviews in Owen *et al*., 2011; Moretti and Ronchi, 2011). For example, fluidisation in saturated sediments is commonly attributed to water escapes associated with overloading of a sequence upon the rapid emplacement of turbidites (Keunen, 1958; Moretti and Ronchi, 2007). Such a mechanism would be in keeping with the Charnian depositional environment (Moseley and Ford, 1989; Carney, 1999); however, the downwarped structures featured in Figs 3a and b were clearly formed *after* a major episode of sediment-gravity flowage (the Sliding Stone Slump Breccia Member; Fig. 2), and there is no evidence for a similar event occurring close above them.

As noted by Montenat *et al*. (2007), there are cases where the identification of seismites remains hypothetical through a lack of complete knowledge of the geological context. Similarly, Pirrotta and Barbano (2011) suggest that the causative mechanism for soft-sediment deformation structures is generally not directly recognisable by the analysis of their morphologies; it requires a paleoenvironmental reconstruction of the site, at the moment of the sediment deposition, and a critical analysis aimed at excluding the other causes. It is therefore often more feasible to recognise seismically-triggered soft-sediment structures in modern earthquake zones, and when this is done features that include thixotropic wedges are commonly identified (*e.g.* Thorsson *et al*., 1986; Pirrotta and Barbano, 2011). Where contemporary seismicity cannot be established, one criterion in favour of a seismic origin, cited by Moretti and Ronchi (2011), is where undeformed beds identical in lithology and facies to the deformed horizon occur above and below it. This is the case for the observed structures in Bradgate Park, which are both underlain and overlain by relatively undisturbed strata (Fig. 3a).

The possibility that some structures described as thixotropic wedges may in fact be ice-wedge casts, which are of similar morphology, has been considered by many workers. However, such an origin can usually be ruled out when climatic, morphologic and chronological lines of evidence are introduced, as discussed by Thorsson *et al*. (1986). For the Bradgate Park structures a glacigenic origin can be more easily dismissed. Ice-wedge casts are commonly held to form through a process of thermal contraction accompanied by seasonal melting and freezing in permafrost environments, although the precise mechanisms are not as yet fully understood (*e.g.* Murton and Kolstrup, 2003). The Bradgate Park structures, however, formed in water-saturated sediments deposited on the floor or lower slopes of a marine turbidite basin in which palaeotemperatures would not have been significantly affected by short-term fluctuations.

Conclusions

The downwarped structures in the Charnian Supergroup at Bradgate Park strongly resemble 'thixotropic wedges'; a type of soft-sediment deformation structure falling within the category of 'seismite' according to Montenat *et al*. (2007). Seismites can arise within a water-saturated sediment column that has inherent thixotropic properties such that, when shaken during an earthquake of sufficient magnitude, it becomes mobilised due to the complementary processes of liquefaction and fluidisation.

This origin for the Bradgate Park downwarped structures is in accordance with suggestions that seismicity is one of the main triggering mechanisms for generating a whole range of soft sediment deformation phenomenon in turbidite basins (Montenat *et al*., 2007). Although many of the supposed seismogenic disturbances reviewed by those authors are found in the Charnian Supergroup, it is accepted that for ancient rock sequences the involvement of seismicity will always be difficult to prove, relying as it does on circumstantial rather than conclusive evidence. A seismically active, island arc-type environment is, however, in keeping with the nature of massive andesitic and dacitic igneous rocks interpreted to represent contemporary volcanic centres in the north-western part of Charnwood Forest (Moseley and Ford, 1989; Carney, 1999).

One non-seismic cause of instability within turbidite basins which should be considered is overloading of the sedimentary sequence due to rapid deposition of the beds above, as pointed out by Moretti and Ronchi (2011). If the Bradgate Park downwarped structures are indeed 'seismites' *sensu* Montenat *et* al. (2007), this mechanism may not be applicable; however, a holistic approach, which includes the possibility of both seismic and non-seismic triggering factors, would be advisable when attempting to explain the many other types of soft-sediment deformation seen in Charnian strata.

Following from this, a possible sequence of events for the passage of sedimentation shown in Fig. 2 is that, firstly, part of the Charnian sedimentary sequence became destabilised, either through seismicity or overloading, or a combination of both. This caused a major slide to develop on the submarine slope, resulting in the disaggregation and widespread gravity flowage of unconsolidated sediments, to be emplaced as the Sliding Stone Slump Breccia Member. Subsequent seismic activity may have been the more direct cause of limited fissuring and mobilisation within an overlying package of thixotropic sediments, forming the downwarped structures described here.

Acknowledgements

The author is grateful to Shilpa Patil Pillai and Claudia Pirrotta for discussions and donation of the images respectively shown in Figures 4a and 4b. I also thank BGS internal reviewers Colin Waters and Phil Wilby, and the journal reviewer Trevor Ford for their valuable comments on various drafts. This paper is published by permission of the Executive Director, British Geological Survey (NERC).

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Derby dust: geochemical characterisation of airborne inorganic particulate matter in western Derby

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Abstract: We report the results of a pilot study, carried out at the University of Derby during 2010 on the nature of the inorganic particulate matter in the air in west Derby. We have found three chemically distinct groups of particles. 1: Sulphates, including Ca-sulphates (Gypsum), Na-sulphates and mixed grains in which sulphate has nucleated on a silicate host, which reflect a combination of anthropogenic and natural processes; the sulphate may be derived from industrial areas around the Bristol Channel or more locally from the A38 road adjacent to the sampling site. 2: Phosphate-silicate compounds that may be derived from fertilisers or from the local crematorium. 3: A variety of silicates, including quartz and feldspar, of natural origin but not necessarily of local provenance, and also an unusual anthropogenic iron-rich silicate. We conclude from a study of the measured compositions, grain shape and grain size that they are not harmful to human health.

Atmospheric dust affects us in a variety of ways. Within the atmosphere it exerts an influence on climate and weather patterns, and more rarely, may be a hazard to travel. Near the Earth's surface dust contributes to the transport of allogens and pathogens and is implicated in some respiratory diseases. In Britain it has been suggested that 'any air sample… will include minerals derived from rocks, soils and construction… sulphates… chlorides…..elemental and organic carbon…. biological and other organic compounds… iron compounds and a range of other metals' (Moreno *et al*., 2004). Thus in the East Midlands we might expect dust from natural sources, such as soils, and from anthropogenic sources such as quarrying, construction, industrial processes and from traffic.

We report here the results of a pilot study, carried out at the University of Derby during 2010, on the nature of the inorganic particulate matter in the air in west Derby. Most dust studies have the particle size distribution, the mass of dust collected and the bulk composition as their primary focus. Only a few studies have focussed on the chemical composition of individual dust grains (Moreno *et al*., 2004). Our aim therefore was to analyse the dust particles collected, under the scanning electron microscope (SEM), with a view to understanding the chemical composition of the dust at a grain scale and to attempt to establish the origin of the dust. Only samples greater than about 2 microns in diameter were examined. Whereas smaller particles pose a potential health risk (Price *et al*., 2010), they are not easily analysed under the SEM and so were excluded from this study.

Thirty four air samples collected during this project were investigated on the scanning electron microscope (SEM) at the University of Derby; 106 images were recorded and 113 grains were chemically analysed. The chemical data are used to characterise the particles, make inferences about their provenance and draw some tentative conclusions about their potential consequences for human health.

Air sampling

The University of Derby has a long tradition of air sampling and has been operating spore traps on behalf of the Midlands Asthma and Allergy research Association for many years (Ryall *et al*., 2002). However, this study is the first attempt to quantify the composition of inorganic dust grains in Derby. Atmospheric air was collected continuously for eight hours each day on 34 selected days through the months of April to August 2010. The sampling site, now relocated from the University Mickleover site, was on the roof of the University of Derby library (SK340379), at a height of 14.5 m above the ground. This location is outside the city of Derby, in an area completely devoid of major industrial atmospheric pollution, although the A38 trunk road, which runs in a road-cutting about 7 m deep, is about 60 m away.

A Bukard air sampler was used with an intake of about 10 litres per minute (human breathing rate). Samples were collected onto a 2.5 mm diameter adhesive disc, stuck on a masked microscope slide, which moved vertically at a rate 3 mm/hr. This allowed an eight-hour sampling run normally collected between 9:00am and 7:00pm. Meteorological conditions were obtained from the University's Geographical Sciences' automatic weather station (at SK338378). This utilises a Campbell CR10X data logger and is fully compliant with UK Meteorological Office standards. Mean wind direction for each day was computed from the mean of measurements every 10 minutes during the sampling period (Table 1).

Geochemical analysis

The microscope slides were carbon sputter coated and examined using a LEO 1450VP SEM (Zeiss) scanning electron microscope (SEM) at the University of Derby. The electron beam was operated with an accelerating voltage of 20 kV and a beam current of 50 mA. In order to eliminate the possibility of sputtered

Sample No	Date 2010	Wind direction (deg)	Wind speed (m/s)	Atmos pressure (mbar)	Mean temp (°C)
0	13/04	131	4.76	1012.67	10.59
1	19/04	88	4.21	1003.78	7.83
2	20/04	304	7.93	1004.70	9.63
3	21/04	209	2.85	1007.00	9.62
5	23/04	114	4.47	1001.50	14.21
6	26/04	293	5.65	1010.50	15.63
7	27/04	245	4.72	1012.20	16.98
9	17/05	305	4.83	1010.20	14.80
10	18/05	125	2.31	1014.40	16.90
11	19/05	209	3.92	1014.80	17.71
12	20/05	185	2.31	1017.80	20.77
13	01/06	159	2.16	1002.10	13.10
14	02/06	213	2.48	1009.00	17.52
15	28/06	256	4.54	1005.50	22.99
16	29/06	309	5.02	1004.78	22.34
17	30/06	234	3.20	1003.90	22.32
18	05/07	301	5.19	1008.50	18.70
19	06/07	222	4.12	1007.33	20.08
20	08/07	250	3.82	1003.67	20.68
21	09/07	244	5.25	1002.00	24.00
22	14/07	165	4.79	986.11	18.46
23	15/07	221	7.30	988.67	19.22
24	16/07	246	5.97	993.50	17.97
25	19/07	214	5.13	1003.89	24.15
26	20/07	220	2.60	993.50	22.05
27	21/07	225	3.48	991.25	20.26
27a	23/07	197	1.44	1008.25	17.40
28	29/07	295	5.39	1002.89	16.60
29	03/08	257	4.31	1000.00	19.35
30	04/08	272	4.63	993.63	16.20
31	06/08	198	5.52	997.13	18.94
32	09/08	202	4.70	997.38	19.76

***Table 1**. Samples' dates and weather conditions.*

silicon contamination from the slide a control slide was similarly prepared. The slides were placed on the SEM stage under vacuum and grains were analysed using an Oxford Instruments Inca CS-138284 energy dispersive spectrophotometer capable of an analytical spot size of 1 micron. Most analyses were made by rastering an area within the grain a few microns across. This detector characterises the secondary X-rays from the analysed grains and converts the data into elemental concentrations. Software, typically used for the analysis of gunshot residue, was set to automatically examine a series of randomly selected areas for particles and to characterise each according to the combination of elements found. The software was set up to find particles with an inorganic composition and in particular silicates, since these are the most common substances of geological origin. The chemical composition of individual grains was re-calculated as oxides and normalised to 100%, allowing comparisons to be made with common rocks and minerals (Table 2).

Following each sample run, the software allowed relocation of specific particles or areas in order to obtain high resolution images of specific grains (Fig. 1). From these, estimates of the shape and size of individual grains were made.

Sample compositions determined from the SEM were used in combination with the size of the particles and the wind direction to assess their likely provenance. We explore the likelihood of dust grains being of natural origin; this is assessed from their composition and its correspondence to that of natural minerals and rocks. Grains with compositions that are not consistent with a mineralogical origin are thought to be anthropogenic.

Geochemical results

Three main groups of particles were identified on the basis of their chemical composition: those rich in or containing sulphur, those rich in or containing phosphorus, and those rich in silicate. There is overlap between all three groups. These three groups were identified because, whereas silicates are the most common naturally occurring materials, phosphates and sulphates are not. These latter two groups therefore are of interest because of their unusual provenance. Previous studies do not report the presence of phosphates (Moreno *et al*., 2004; Giere and Querol, 2010).

Few particles are less than 5 µm in diameter, and most are in the range 5-10 µm so in terms of human health are classified as coarse particles. Typically particles of this size come to rest in the tracheo-bronchial region (Giere and Querol, 2010).

Sulphur-bearing particles

Thirty-five of the 113 analysed particles contain sulphur, and these were recorded consistently throughout the duration of the study. Concentrations vary between 3.8 and 68% sulphur expressed as SO_3 (Table 2). They are 5-50 µm in size, with most 5-10 µm. There is a variety of particle shapes; some grains are composite grains made of smaller particles, some are rounded and others angular or acicular (Fig. 1a and b).

From the chemical compositions samples in this group may be identified as

- pure sulphates; these grains are 5-10 µm in diameter and comprise Ca-sulphate (gypsum and anhydrite), Ca-Na-sulphates and Na-sulphates (Fig. 2a);
- mixed particles that contain a silicate and a sulphate component (Fig. 2a and b);
- mixed particles that also include a phosphatic component (5-18% phosphorus expressed as P_2O_5) and one particle that is almost exclusively sulphur and phosphorus (Fig. 2d).

The mixed silicate-sulphate particles have variable compositions, but define mixing trends on a plot of

	Sample No	size (µm)	shape	SiO_2	TiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O	P_2O_5	SO_3	Total
Silicate														
very high Fe	27a	30	composite rounded	29.53	0.00	26.45	31.48	12.54	0.00	0.00	0.00	0.00	0.00	100.00
very high Fe	27a	40	composite rounded	29.74	0.00	26.93	31.74	11.59	0.00	0.00	0.00	0.00	0.00	100.00
very high Fe	3	10	angular	31.73	0.00	22.34	41.14	2.94	1.84	0.00	0.00	0.00	0.00	99.99
very high Fe	12	25	elongate	33.51	0.00	21.80	27.14	17.55	0.00	0.00	0.00	0.00	0.00	100.00
very high Fe	10a	10	equant	33.79	0.00	26.29	27.76	12.17	0.00	0.00	0.00	0.00	0.00	100.01
basalt ?	5b	10	elongate	45.41	0.00	20.49	17.12	14.73	2.24	0.00	0.00	0.00	0.00	99.99
basalt ?	14f	10	angular	49.09	0.00	26.76	11.65	12.50	0.00	0.00	0.00	0.00	0.00	100.00
basalt ?	0	20	composite	47.01	4.74	8.56	19.72	11.42	8.55	0.00	0.00	0.00	0.00	100.00
basalt ?	1	5	angular	47.65	0.00	15.28	16.52	8.77	11.79	0.00	0.00	0.00	0.00	100.01
andesite	0	6	rounded	60.43	0.00	8.30	11.30	8.72	11.26	0.00	0.00	0.00	0.00	100.01
andesite	0	20	composite	62.05	0.00	11.21	10.02	7.36	9.36	0.00	0.00	0.00	0.00	100.00
granite ?	11c	25	aggregate	68.73	0.00	12.08	9.51	0.00	5.54	0.00	4.13	0.00	0.00	99.99
granite ?	11d		composite	70.77	0.00	18.72	6.06	0.00	4.45	0.00	0.00	0.00	0.00	100.00
K-feldspar	32b	5	irregular	57.05	0.00	30.75	0.00	0.00	0.00	0.00	12.19	0.00	0.00	99.99
K-feldspar	27a	6	angular composite	65.00	2.29	16.40	0.00	0.00	0.00	0.00	16.31	0.00	0.00	100.00
	14d	5	rounded	62.18	0.00	32.56	0.00	0.00	0.00	0.00	5.26	0.00	0.00	100.00
Plagioclase fel	17b	5	angular	61.09	0.00	12.15	0.00	0.00	26.77	0.00	0.00	0.00	0.00	100.01
Ca-sil	15a	15	angular composite	68.64	0.00	0.00	0.00	0.00	31.36	0.00	0.00	0.00	0.00	100.00
quartz	14c	5	rounded	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	100.00
quartz	19a	5	angular	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	100.00
quartz	17f	10	angular composite	88.79	0.00	6.16	2.98	0.00	0.00	0.00	0.00	2.08	0.00	100.01
Sulphate														
sulphur-silica phosphorus	30b	5	needle	14.45	0.00	0.00	3.16	0.00	29.12	0.00	0.00	8.46	44.82	100.0
sulphur-silica phosphorus	30c	5	needle	6.44	0.00	0.00	0.00	0.00	0.00	0.00	0.00	55.70	37.86	100.0
sulphur-silica phosphorus	31a	10	composite	40.34	0.00	20.16	8.47	0.00	8.10	0.00	2.19	6.76	13.98	100.0
sulphur-silica	7	10	angular	44.82	0.00	24.95	7.16	8.04	2.76	0.00	5.91	0.00	6.37	100.0
sulphur-silica	25c	5	angular	63.19	0.00	0.00	0.00	0.00	2.48	11.24	0.00	0.00	23.10	100.0
sulphur-silica	25d	10	composite	20.45	0.00	7.43	3.21	0.00	23.88	0.00	0.00	0.00	45.02	100.0
sulphur-silica	31e	7	angular	70.25	0.00	15.09	0.00	0.00	2.74	0.00	4.74	0.00	7.18	100.0
Feldspar and gypsum	31f	7	angular	70.09	0.00	13.48	0.00	0.00	2.50	0.00	5.04	0.00	8.90	100.0
Na- sulphate	23a	6	angular	0.00	0.00	0.00	0.00	0.00	4.26	39.12	0.00	0.00	56.62	100.0
	30a	5	angular	0.00	0.00	0.00	0.00	0.00	4.75	33.57	0.00	0.00	61.68	100.0
	22(2)	5	rounded	0.00	0.00	0.00	0.00	0.00	0.00	32.05	0.00	0.00	67.95	100.0
Gypsum	14e	8	rounded	0.00	0.00	0.00	0.00	0.00	40.18	0.00	0.00	0.00	59.82	100.0
	23c	5	rounded	0.00	0.00	0.00	0.00	0.00	42.25	0.00	0.00	0.00	57.75	100.0
Phosphate														
Phosphatic	1a	8	composite	47.58	2.01	11.97	11.81	3.79	9.27	0.00	0.00	4.94	8.63	100.0
Phosphatic	12 part 2	5	rounded	81.15	0.00	9.15	0.00	0.00	0.00	0.00	0.00	9.70	0.00	100.0
Phosphatic	13 (3)	10	angular	0.00	0.00	20.84	13.18	0.00	29.37	0.00	0.00	36.60	0.00	100.0
Phosphatic	15d	5	needle	0.00	0.00	0.00	0.00	0.00	13.46	25.46	0.00	11.14	49.93	100.0
Other														
Dolomite	28b	80	angular	0.00	0.00	0.00	0.00	42.49	57.51	0.00	0.00	0.00	0.00	100.00
Fe-metal	25a	5	rounded	0.00	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00	100.00

***Table 2**. Representative chemical analyses (as weight percent oxides) in dust grains from west Derby. Zero values mean no detection on the SEM.*

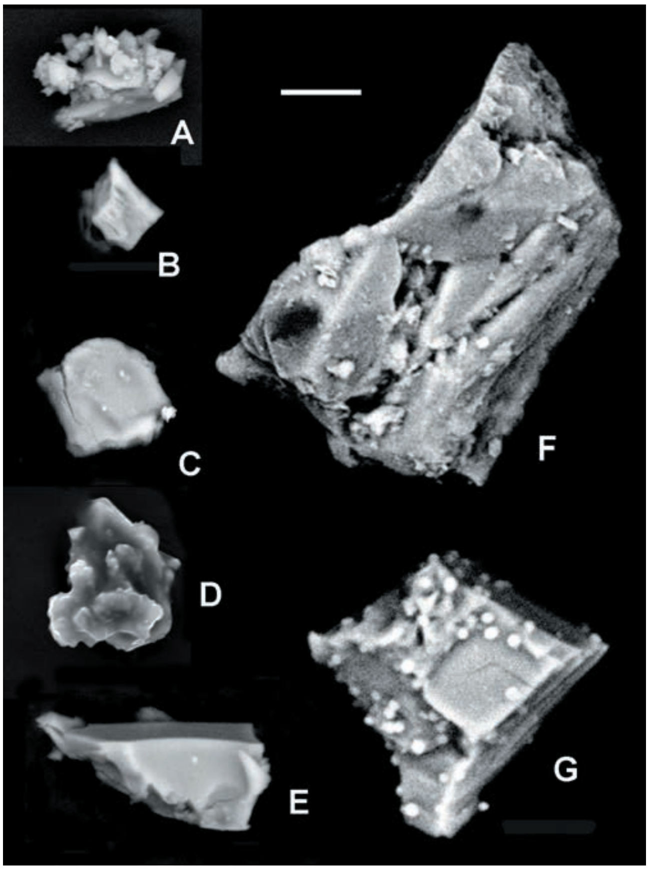

***Figure 1**. Secondary electron images of selected particles from the scanning electron microscope. A = silicate-sulphate; B = basalt; C = high-iron silicate; D = silicate-carbonate; E = calcium silicate; F = quartz; G = carbonate. All to same scale, bar scale is 10 microns long.*

Ca+Na vs sulphate plot (Fig. 2a) and a silicate-sulphate plot (Fig. 2b) implying that silicate particles are mixed to a varying degree with Ca- and Na-sulphates. The silicate component of these particles is thought to be natural, from silicate rocks, and a variety of different silicate sources are indicated. The mixed particles including phosphorus are discussed below.

Phosphatic particles

A second group of 17 chemically distinctive particles are those containing 4-37% phosphorus expressed % P_2O_5 (Table 2). They vary in size from 5 to 20 µm although most are between 5-10 µm. Some are composite grains; others show an angular, rounded or acicular form. These grains are variable in composition and show the following features:

- One grain has high P_2O_5 (36.6%) and contains CaO in equal molecular proportion; Al and Fe are present in the atomic ratio 2:1. It is likely to be a chemical mixture, part of which is made up of Ca-phosphate.
- Most other samples contain silica and show a weak positive correlation between the silica content and the phosphorus content (Fig. 2d).
- Some phosphatic particles contain sulphur (as noted above). Two groups (Fig. 2c) are distinguished by sulphur that is low (<21% SO_3) or high (>40% SO_3).

Silicate particles

More than half the particles analysed are rich in SiO_2 (Table 2). Some are entirely silicate:

- Quartz: 5-30 µm in diameter, rounded or angular, some single grains, but the larger ones made up of multiple grains of quartz.
- Feldspar: 5-25 µm in diameter; both potassium feldspar and plagioclase have been identified.
- Individual grains of Ca-silicate (15 µm across and angular), Fe-alumino silicate (5 µm across as multicrystal aggregates), and two grains of granitic material one of which is a 25 µm rock fragment high in SiO_2 (ca 70%) but also very high in FeO.

There is also a group of particles (5-40 µm) with variable morphologies including angular, elongate, rounded and composite. They containing very high Fe (19-41% FeO), but are low in SiO_2 (29-41%), which is less than is normal in silicate rocks. Al_2O_3 contents are high, as is MgO in most grains. Two grains with lower FeO and higher SiO_2 and more basaltic chemistry may also be part of this association. Natural silicate rocks containing more than 20% FeO are most unusual and are virtually unknown in Britain. These silicate particles show a strong negative correlation between FeO

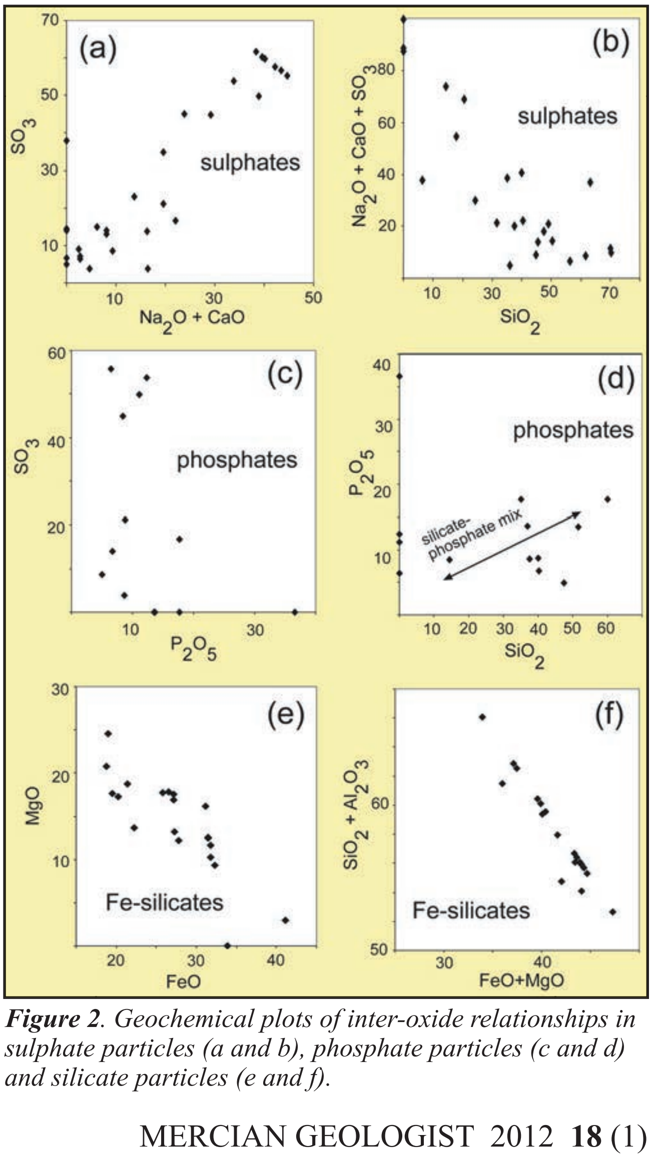

***Figure 2**. Geochemical plots of inter-oxide relationships in sulphate particles (a and b), phosphate particles (c and d) and silicate particles (e and f).*

and MgO and a strong negative correlation between (FeO+MgO) and (SiO_2+Al_2O_3), implying substitutions between Al-Si and Mg-Fe end members (Fig. 2e and f). Mineralogically, they are closest to the composition of garnet, which does not occur naturally in this area. Price *et al*. (2010) reported particles rich in Fe and Mg in association with urban traffic in Swansea and Wang *et al*. (2003) proposed that elevated metal concentrations are related to diesel emissions. However, neither source describes these particles as silicates, and their origin remains uncertain.

We considered the possibility that these particles might be power station fly-ash; although their high SiO_2 and Al_2O_3 contents would support this view, fly-ash is not normally iron-rich, and its particles are commonly spherical, which these are not. We also considered that some silicate might be related to asbestos. However, natural asbestos is typically magnesian, not iron-rich, and there were very few fibrous particles of any type in our sample set.

The sample collection period overlapped with the eruption in April 2010 of the Icelandic volcano Eyjafjallajökull. Samples 0, 1 and 2 (collected between April 13 and 20) are of basaltic and andesitic composition, and so may be volcanic ash from Iceland. A positive identification of Icelandic ash in Loughborough was made at the British Geological Survey in dust collected on 20th April 2010 (www.bgs.ac.uk/research/volcanoes/icelandic_ash) and there are some chemical similarities between one grain of 'basaltic composition' in this study and tephra reported from Iceland (Sigmarsson *et al*., 2010). An indicator of these distinctive compositions is measurable TiO_2 in some grains. However, our imaging does not show characteristic tephra morphologies. Single grain and multi-grain aggregates are up to 20 μm in length.

Other compositions

A small number of other particles included iron oxide (three 5 μm grains of 100% FeO) and dolomite (two 50-80 μm grains with equal proportions of MgO and CaO).

Provenance of the particles

The dust particles' provenance may be local or distant, anthropogenic or natural. Our analysis is governed by the prevailing wind direction during the sampling period, which was predominantly from the SW (Table 1), coupled with consideration of the geology of the English Midlands.

Sulphates

Sulphur dioxide is a common constituent of atmospheric gases. It is the product of combustion in car engines and in power stations, and may also be carried inland with sea-spray. These sources give rise to the formation of Ca-sulphates (Giere and Querol, 2010) and also Na-sulphates. Evidence for mixing between silicate materials and sulphates suggests that Ca- and Na-sulphates may nucleate on silicate particles in the atmosphere. Thus, the sulphur-bearing silicate particles are produced through a combination of anthropogenic processes (combustion of fossil fuels) and natural ones (silicate nuclei). It is not possible to identify the source of the sulphur, though the prevailing wind direction comes from industrial areas around the Bristol Channel. A more local source, the A38 road, is also possible. The mixing trend in Figure 2b points to end-member silicates with 50-70% SiO_2; these cover the range of igneous rock compositions from basalt to granite. There are, however, few local sources.

Phosphates

Naturally occurring phosphates are very rare. However, they are contained in fertilisers, where they are often associated with sulphur. In this study the phosphatic particles were mostly derived from between the west and south. The other possible source of Ca-phosphates is bone, and it is worthy of note that Derby Crematorium lies 1 km due west of the sampling site. Given the comparative rarity of phosphates in the natural environment, this very local source may be the origin of these particles.

Silicates

A plot of (Mg+Fe+Al+Si)/Si vs Al/Si plot subdivides the silicate mineral grains into felsic and mafic groups (Fig. 3). Our data are more representative of the rural sample set from Cornwall (Moreno *et al*., 2004), with fewer intermediate compositions and more mafic compositions than is found in the urban data set from Port Talbot, Birmingham, London and Sheffield.

Quartz is a very common natural material. It is present in the rocks and surficial deposits of the Midlands and might be released in local quarrying operations. However, Saharan dust is also well known in Britain (Ryall *et al*., 2002), so for very small grains (<10 μm) the provenance is not necessarily local.

Potassium feldspar would indicate a granitic provenance. Local sources are found southeast of

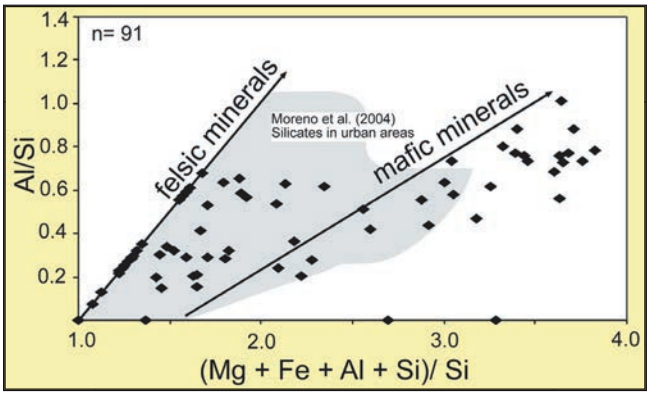

Figure 3*. (Mg+Fe+Al+Si)/Si vs Al/Si plot for silicate grains compared with silicate in other urban areas (grey shaded area) (after Moreno et al., 2004).*

Derby in the Charnwood Forest area, where there is active quarrying. However, the wind directions suggest a more westerly source, which is difficult to identify.

Individual grains of a Ca-silicate and a Fe-alumino silicate could be natural. The grains of granite material do not match precisely the felsic rocks from the Charnwood area, which are granodiorites and quartz diorites where high FeO is atypical. The origin of the Fe-Mg rich alumino-silicates is a puzzle. They are abundant and derive from the west and south. Mineralogically they are close to the composition of garnet, but garnet does not occur naturally in this area. These particles are most probably the product of diesel emissions, or are related to an unknown industrial process. The conclusion that these particles are not of natural origin is consistent with their distribution on the mineral composition diagram in Figure 3, where they plot at relatively high levels of Al/Si but with very high (Mg+Fe+Al+Si)/Si values and are more Fe-Mg rich than typical mafic minerals.

Other compositions

Dust associated with limestone quarrying is produced northwest of Derby. Some of the grains recorded may be thus derived. Other grains appear to have come from the south and are not locally derived.

Implications for respiratory pathology

All but one of the particles examined in this study was less than 50 µm in diameter and so will be removed in either the naso-pharyngeal or tracheobronchial region. Most are 10 µm or less and so the majority will be removed in the tracheobronchial region. These include the Na- and Ca-sulphates, the mixed sulphate-silicate grains, phosphorus-bearing silicates, quartz, feldspars and the high-Fe silicates. Our analysis of grain shape shows that only a small number are acicular or angular and so potentially harmful to the lungs. The majority of grains are rounded or composite in nature, and are therefore benign.

Although phosphate is commonly involved in pathological tissue mineralization, its health implications are not well known (Heaney and Banfield, 1999). However, there is very little evidence to suggest that it is a serious health hazard, and there is no legislation to control its emission into the atmosphere. Similarly there are no known toxic effects from gypsum. Silica (SiO_2) and silicates, on the other hand can cause silicosis if there is exposure to very high concentrations (Ross *et al.*,, 1999) although the abundances noted here are very low.

Acknowledgements

This study was funded by a grant from the Midlands Asthma and Allergy Research Association, which is gratefully acknowledged; two anonymous reviewers are thanked for their comments.

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The Holocene 8200 BP event: its origin, character and significance

Colin A. Baker

Abstract: A considerable volume of palaeoclimatic research has emerged in the last 20 years since the initial publication of the Greenland ice core records. This review focuses on the pattern of Holocene climate change that includes a remarkable oscillation in the so-called 8.2 ka BP event. The footprint of this is tracked across the North Atlantic, from its spectacular origins in the Hudson Bay megaflood, to the Greenland ice sheet, and on into Western Europe and beyond. Researchers are unanimous in recognising a sharp temperature downturn in this anomaly, but differ in their understanding of its impact on precipitation. A hypothesis of cold aridity is proposed, and the paper concludes with a speculative look into the future.

It is almost 20 years since the first publication of the Greenland GRIP ice core records by the Danish palaeoclimatologist, Willi Dansgaard. At the same time, Wally Broecker at Columbia's Lamont-Doherty Earth Observatory was developing the concept of the global ocean conveyor and proposed ice-rafted debris horizons in Atlantic seabed sediments. Rapid climatic change became an important focus, with as many as 25 Dansgaard-Oeschger cycles in the ice core oxygen isotope records corresponding to Heinrich iceberg events in the oceanic records throughout the Late Pleistocene (Fig. 1).

Our current interglacial period (Holocene) displays little variability in these palaeoclimatic records, whereas the preceding glacial period (Devensian) is noted for frequent and abrupt spikes with $\delta^{18}O$ amplitudes of 3-5‰ implying temperature swings of 8°C or more (Fig. 1) sometimes within only a few decades. Decadal oscillations like these were clearly not the expression of the Milankovitch pace-maker (Lee, 2011), and the search was on for what alternative mechanism might have been responsible. One possible hint came from the rock debris recovered from the Heinrich layers, whose primary source appeared to be Hudson Bay. Could there be a causal link between glacial meltwater released from the waning Laurentian Ice Sheet and the Atlantic Ocean conveyor circulation? And how did ocean-atmosphere coupling operate to transfer these perturbations to the atmosphere above the Greenland ice sheet?

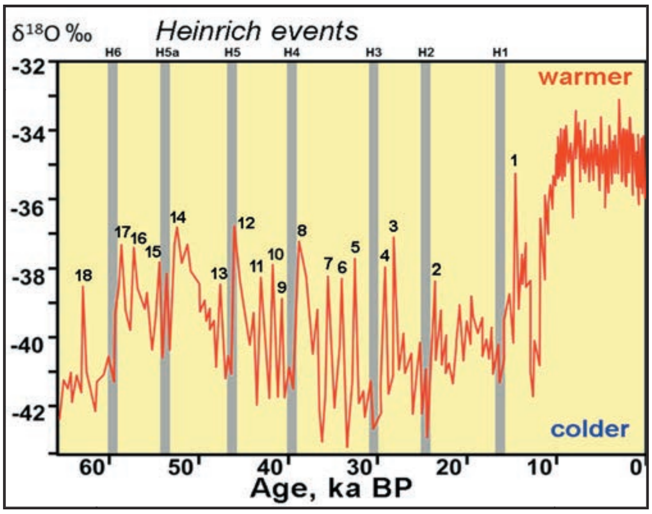

Figure 1. Climate changes for the interval from 65 ka to the present, from the Greenland Ice Sheet Project (GISP2) $\delta^{18}O$ record (after Stuiver and Grootes, 2000); the more positive values correspond to warmer conditions. Numbers 1-18 identify the warm peaks of the Dansgaard-Oeschger oscillations; grey bars are the Heinrich events, H1-H6 (after Delworth et al., 2008).

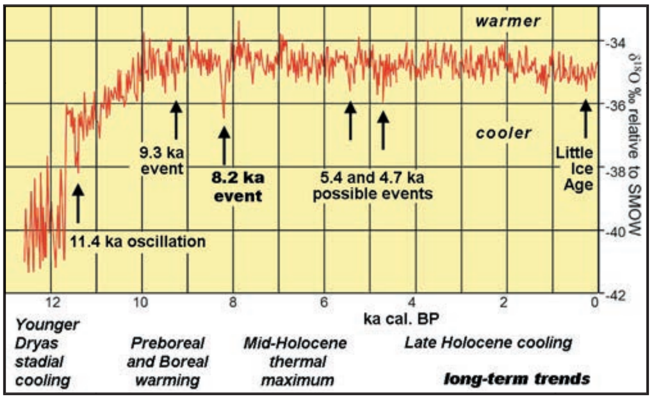

Figure 2. Holocene palaeotemperature reconstruction for Greenland, from GISP2 (after Stuiver and Grootes, 2000).

Examination of the Holocene record in three Greenland ice cores (GRIP, NGRIP and GISP2) was undertaken by Richard Alley and colleagues in 1997, whose explanatory hypothesis has proved particularly fruitful in stimulating a new wave of palaeoclimatic research. Investigating this concept of rapid climate change was driven in part by an IPCC agenda, and sparked immense media interest; the scenario of Atlantic conveyor shutdown was, and remains, a "hot" topic. Alley *et al.* (1997) were the first to identify the so-called 8.2 ka event, a striking climatic anomaly in the otherwise stable profile of the Holocene ice oxygen isotope record (Fig. 2). Numerous studies confirm this to be the most extreme and best defined signal in the whole Holocene. A chain of 8.2 ka BP events is traceable across the North Atlantic, from the Hudson Bay to Greenland to Western Europe, the Mediterranean and beyond (Fig. 3).

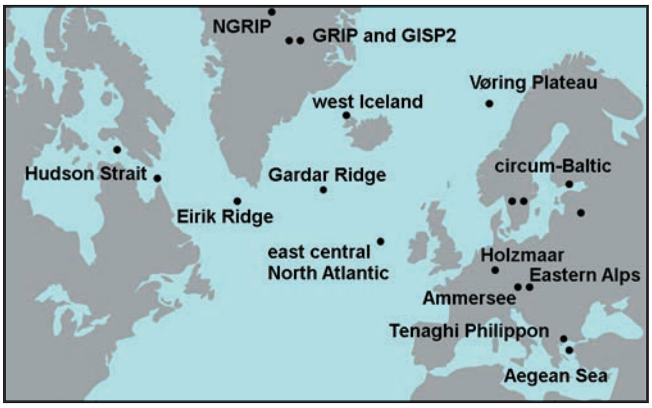

***Figure 3**. Locations in the North Atlantic and Europe.*

Glacial Lake Agassiz's megaflood

During the Late Pleistocene and Early Holocene the last remaining North American ice sheet impounded its largest-ever glacial lake, the combined Lake Agassiz-Lake Ojibway, covering an area of about 1.5M km² (Fig. 4). It produced intermittent outbursts through the Mississippi, McKenzie, St Lawrence and Hudson spillways. Partial collapse of ice and meltwater discharge is believed to have generated the Younger Dryas relapse (Lee, 2011). Inevitably, the failure of the last vestige of Laurentian ice released a huge surge into the Labrador Sea and North Atlantic via the Hudson Strait. Dyke (2004) describes this final drainage as a surge of "catastrophic" proportions – a megaflood. A date of 8470±300 cal years BP is widely quoted for this spectacular event. With a rather large error margin, this figure is in fact a compound date based on ten separate radiocarbon measurements. Barber *et al*. (1999) clarify how these were obtained from marine carbonate, collected below and above a red bed marker horizon, within the Hudson Strait channel. Final flood escape is thus constrained between 8580 BP (below) and 8400 BP (above); with 95% probability error margins, a range of dates between 8740 and 8320 is possible, and a further dating in James Bay extends this to 8160 BP.

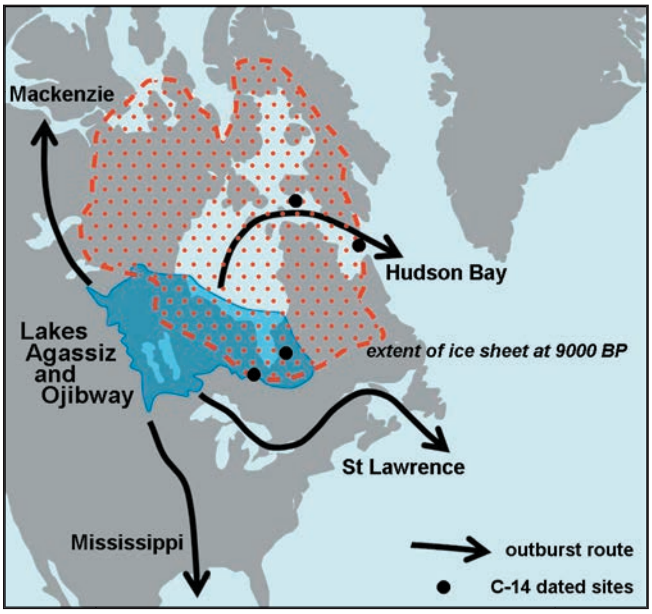

***Figure 4**. Lake Agassiz and the routes of its overflow and outbursts (after Barber et al., 1999; Teller et al., 2002).*

All dates given in this paper are in calibrated years BP; they quote relevant authors' figures only where thus calibrated; otherwise, dates have been adjusted using IntCal09 (OxCal version 4.1).

The estimated volume of meltwater released from Lake Agassiz is the subject of some conjecture; figures vary from 50,000 to 500,000 km³, though Teller and Leverington's (2003) estimate of 160,000 km³ is often used. Clarke *et al*. (2004) estimate peak discharges from the Hudson Strait of between 5 and 10 M m³/sec lasting for up to a year. Put in perspective, the entire global input of freshwater from all present-day rivers into the world's oceans is equal to about 1 M m³/sec, so the term "megaflood" is no exaggeration.

These figures have been used to simulate the likely impact that an outburst would have had on oceanic and atmospheric behaviour (Gregoire *et al*., 2012). A rise in global sea level is calculated at 1.2 m for a volume of 430,000 km³ by Tornqvist *et al.* (2004); Bauer *et al*. (2004) assumed 160,000 km³ over a two-year period, corresponding to a mean sea level rise of 0.5 m, probably accompanied by large gravity waves and increased coastal flooding all around the North Atlantic. While the actual volume remains uncertain, the suggestion of near-instantaneous coastal inundation over a wide area seems entirely credible. There is no evidence for any further massive freshwater release into the North Atlantic after 8000 BP.

North Atlantic freshwater forcing

At about 8.47 ka BP the Lake Agassiz surge coincided with the start of the most pronounced Holocene cold period recorded in the North Atlantic area, the 8.2 ka BP event. Several authors explain this in terms of freshwater forcing, suppressing the normal thermohaline circulation, or, more strictly, the meridional overturning circulation (MOC), which drives the sinking of dense saline surface water, and maintains northward heat transport in the North Atlantic Ocean. Figure 5 illustrates the principal present day overturning, with North Atlantic, Irminger and Norwegian currents conveying warm water northwards, and five inter-connected, deep-water, cold currents carrying dense water southwards; descending convection (or deep water formation) is indicated at three locations. Evidence for slowing of the MOC engine is well documented in the earlier Younger Dryas and Heinrich events, but the Holocene deceleration has only been confirmed more recently.

Several research groups have performed computer simulations to test the MOC engine hypothesis, concluding that a megaflood of Lake Agassiz proportions would indeed have been capable of lowering the surface water density needed to maintain salinity-driven deep water circulation. Freshening and cooling of the North Atlantic would also have greatly increased the extent and thickness of sea ice, contributing further to overall

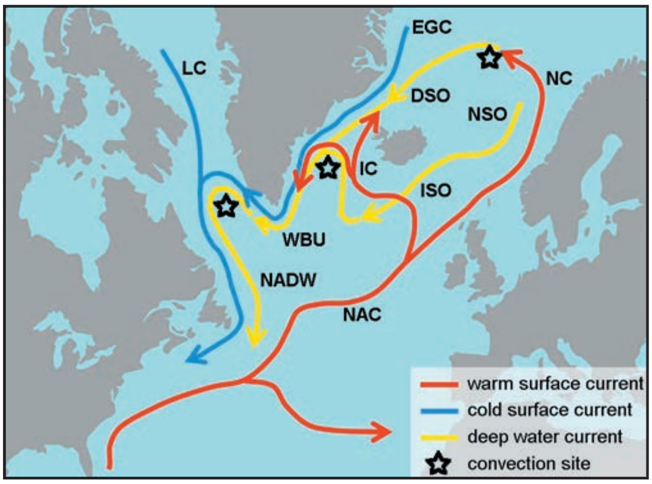

***Figure 5**. North Atlantic meridional overturning circulation (after Kleiven et al., 2008; Delworth et al., 2008; Quillmann et al., 2012). Warm surface currents: NAC = North Atlantic; NC = Norwegian; IC = Irminger. Cold surface currents: LC = Labrador; EGC = East Greenland. Deep water currents: NSO = Nordic Sea Overflow; ISO = Iceland-Scotland Overflow; DSO = Denmark Strait Overflow; WBU = Western Boundary Undercurrent; NADW = North Atlantic Deep Water.*

cooling through positive feedback. Bauer *et al*. (2004) calculate a 40% reduction in MOC, LeGrande *et al*. (2006) reach a similar figure (30-60%), capable of reducing sea surface temperatures by 2-3°C; Wiersma and Renssen (2006) estimate a drop of 5°C in sea surface temperature. Such a scenario could have persisted for many decades.

The palaeo-oceanographic record

Until ten years ago, there was little palaeoceanographic evidence to confirm these theoretical models, certainly none to match the well-documented Younger Dryas and Dansgaard-Oeschger/Heinrich events which had already shown decreases in ocean ventilation and MOC reduction as theory predicted. For the Holocene itself, Bond *et al*. (1999) had already identified cycles of ice-rafted debris (IRD) in the abyssal plain of central east North Atlantic (Fig. 3); Bond event 5 is synchronous with the 8.2 ka BP event, and petrologic tracers pointed mainly to an iceberg source in Greenland and Iceland, with ice-bearing meltwater pushing south well into the path of the warm North Atlantic Current. The authors suggested that the IRD cycles should be regarded as "mini Dansgaard-Oeschger events". In the last ten years at least four research teams (Risebrobakken *et al*. 2003; Ellison *et al*. 2006; Kleiven *et al*. 2008; Quillmann *et al*. 2008) have conducted well-dated high-resolution analyses on deep sea marine cores, using temperature-sensitive foraminifera (Fig. 6). Foram frequency, stable isotope analysis (δ^{18}O and δ^{13}C), chemical ratios and sortable silt fractions have all been employed to reconstruct sea surface temperature, salinity, productivity and bottom water flow speeds.

Both the Eirik and Gardar Ridges (Fig. 3) are sites of contourite sediments, fine-grained seabed sediments deposited and streamlined along ridge contours by bottom-moving currents. Eirik Ridge is followed by the Western Boundary Undercurrent close to the Labrador Sea where the impact of the freshwater pulse must have been initially felt. It was here that Kleiven *et al*. (2006) found a sharp increase of δ^{18}O in *N. pachyderma (s)*, a polar planktonic pelagic foram, confirming the sea surface cooling by ~1.5°C, together with an abrupt decrease in δ^{13}C in the benthic foram *C. wuellerstorfi*, confirming a change in productivity related to decreased ventilation. These abrupt changes, followed by rapid recovery, are dated to a 100-year period between 8380 and 8270 BP. Ellison *et al*. (2006) examined the sortable silt fraction (a proxy for deep current flow speed) in contourite on Gardar Ridge (Iceland-Scotland Overflow), finding a significant decrease between 8450 and 8040 BP, co-registered with an increase of *N. pachyderma (s)* centred on 8290 BP. The influence of the Denmark Strait Overflow has been investigated in West Iceland (Quillmann *et al*. 2008), where Mg/Ca ratios of calcite in the benthic species *C. lobatulus* confirm cooling at around 8200 BP. Today, the Irminger Current carries relatively warm (4-7°C) and saline (35‰) water to Iceland; this was cooled by ~3°C and freshened by ~1‰ for a period lasting 100 years. Further east still, the Risebrobakken team (2003) detected a sharp increase in *N. pachyderma (s)* on the Vøring Plateau west of Norway, suggesting a similar SST decrease of 3°C for a 70-year period. Figure 7 plots these time spans, showing that the cold freshwater pulse from the Hudson Strait must have diffused across the North Atlantic within a 300 year period. This provides strong confirmation of MOC reduction, freshening and cooling as predicted by the simulation models.

The total length of Atlantic cooling (in excess of 300 years) has prompted some observers (e.g. Rohling and Pälike, 2005) to suggest that there may in fact be two forcing mechanisms at work simultaneously – MOC reduction related to the Hudson Bay meltwater discharge, and also background changes in solar radiation. Modelling studies show that changes in insolation alone were not large enough to induce the observed temperature drop over the North Atlantic, therefore meltwater release must have been involved.

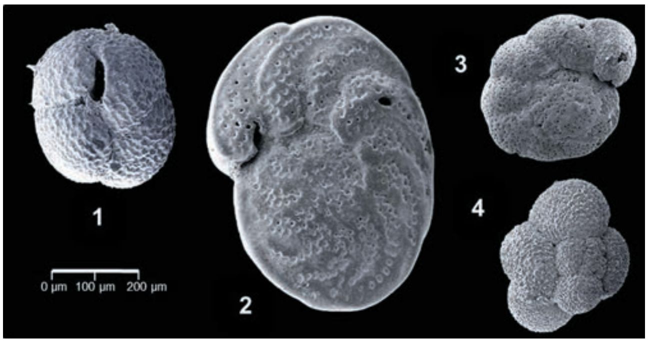

***Figure 6**. SEM images of diagnostic marine foraminifera: 1, Neogloboquadrina pachyderma (s); 2, Cibicidoides wuellerstorfi; 3, Cibicides lobatulus; 4, Globigerina bulloides (from Image Database of Foraminifera.eu-Project).*

The 8.2 ka event in the ice core record

In Greenland, six major deep-drilling projects have been undertaken over the last 40 years (Camp Century, DYE3, Renland, GRIP, GISP2 and NGRIP), the more recent of which provide a remarkably consistent pattern of Holocene temperature fluctuation (Figs. 1 and 2). Periodic cooling events are identified at 11.4 ka, 9.3 ka, 8.2 ka and 0.5 ka BP. Dating of ice cores is achieved principally by layer counting (Fig. 8), but this becomes less reliable with depth as annual layering deteriorates. Greater precision and cross-correlation are achieved by tephrochronology on known volcanic horizons.

Oxygen-isotope ($\delta^{18}O$) variations are a function of air temperature at the time of snowfall, colder episodes being marked by more negative values, since cold snow is depleted in heavier oxygen-18. The degree of cooling is calculated with reference to standard pure water (SMOW). Thus the Younger Dryas stadial (Fig. 2, ~12 ka BP) has a value at or below -40‰, and Holocene values rise to about -35‰ (Fig. 2, ~10 ka BP). Time resolution in the GRIP curve is 50 years, but a finer 20-year resolution is achieved in GISP2. Chronologies of three ice cores (DYE3, GRIP and NGRIP) have been synthesised in a revised timescale (GICC05, Greenland Ice Core Chronology 2005) by employing an improved 5-year resolution (Vinther *et al*., 2006). Such time resolution varies with ice core depth, chosen proxy, and the researchers' choice of running averages to create meaningful trends. Hence a 5-year floating average (using the GICC05 data) was employed successfully by both Thomas *et al*. (2007) and Rasmussen *et al*. (2007) to reproduce the detailed shape of the 8.2 ka BP anomaly.

This most pronounced of all Holocene cold episodes has a $\delta^{18}O$ differential amounting to about half that of the Younger Dryas stadial, but over twice that of the Little Ice Age, prompting Seppa *et al*. (2007) to comment that this was "a unique feature within the last 10,000 years in terms of magnitude and abruptness". Decline in oxygen isotope values is matched by equally dramatic changes in other proxy indicators: a decrease in methane (showing a decline in biogenic sources), an increase in chlorides (showing uptake of sea-salt in a strengthened circulation), an increase in calcium (from continental dust) and an increase in ammonium (signalling greater forest-fire frequency). Thomas *et al*. (2007) also describe low snow accumulation rates in the 8.2 ka BP ice layers (31% lower than the Holocene average). This figure together with continental dust and increased fire frequency points to greater dryness. The 8.2 ka BP downturn was thus both cold and dry. It is this co-registration of six proxies that confirms the profound significance of the climatic reversal (Alley *et al*. 1997; Alley and Agustsdottir, 2005).

At least three studies have succeeded in accurately establishing the timing of the event (Fig. 7). Thomas *et al*. (2007) see the full event lasting 160±5 years, starting in 8247 BP, with an extreme central event of 69±2 years beginning 8212 BP. Slightly earlier figures are reported by Rasmussen *et al*. (2007) with the full event starting 8300 BP, lasting 160 years, and with a shorter 5-year central event. Using methane and $\delta^{15}N$ from trapped air bubbles, Kobashi *et al*. (2007) arrive at slightly later dates, suggesting a rapid cooling and drying at 8175±30 BP that established in less than 20 years, with an extreme cold spell lasting 60 years and a recovery period of 70 years, giving a total duration of 150 years. The combined evidence from these three sources places the climatic anomaly confidently within the period 8300 BP to 8000 BP. Further work on ECM (Electrical Conductivity Measurement) in three ice cores (Vinther *et al*., 2006) has identified fall-out from an Icelandic volcanic eruption located inside the $\delta^{18}O$ minimum, dated at 8236±47 BP, part of an Early Holocene interval characterised by significant increases in volcanic aerosol production (Zielinski *et al*., 1994). This is an important point in the light of suggestions that the 8200 BP event might be thought of as a reliable analogue for future climate change; on the contrary, it may have involved a fortuitous combination of forcing factors (solar reduction, freshwater release and volcanic emissions acting together), and is therefore unlikely to be repeated in the same way in the future.

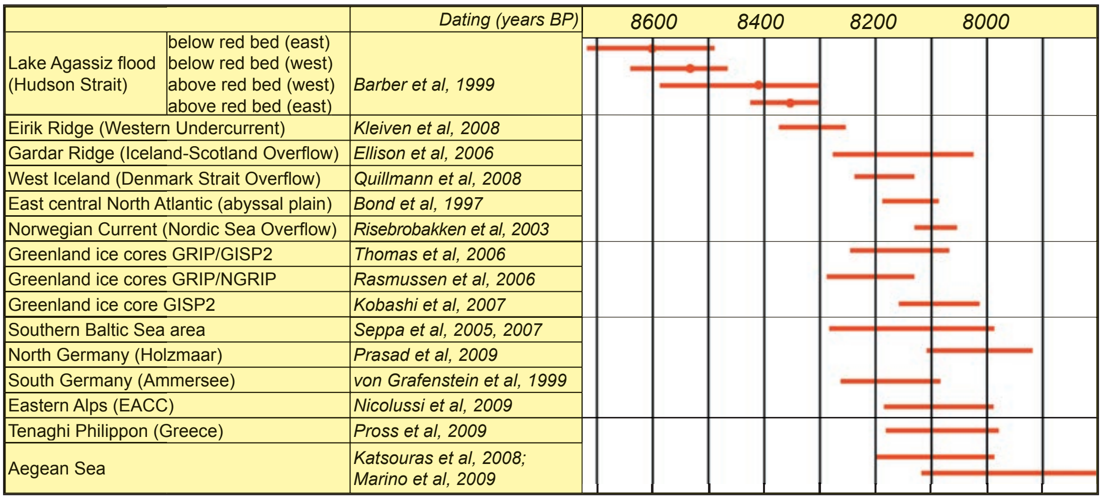

***Figure** 7. Co-ordinated time spans of North Atlantic and European 8.2 ka BP events, as described in the text.*

Cooling in Europe in the 8.2 ka event

Throughout Europe, there is now an improved network of Holocene palaeorecords benefiting from high time-resolution and firm, calibrated, radiocarbon control. Figure 3 displays a selection of such sites from which it has been possible to gauge the likely impact that the North Atlantic anomaly had at 8.2 ka BP.

Seppa *et al.* (2005, 2007) synthesise well-dated pollen records in Scandinavia and the southern Baltic rim, in which hazel, elm and alder decline simultaneously and abruptly between 8300 and 8000 BP south of 61°N. Nicolussi *et al.* (2009) identify a 200-year period of very poor tree growth from 8200-8000 BP in the detailed Eastern Alps Conifer Chronology. Further Alpine evidence is given by Tinner and Lotter (2001) from varved sediments that register a sudden collapse of hazel woodland at around 8.2 ka BP: hazel, normally well-adapted to continental conditions and seasonal drought, appears to have succumbed in less than twenty years. At Ammersee (southern Germany) a long $\delta^{18}O$ profile from benthic ostracods (von Grafenstein *et al.* 1999) provides isotopic evidence of a strong downturn over 200 years, and another high-resolution analysis from Holzmaar, North Germany (Prasad *et al.* 2009), detects a 180-year anomaly with remarkable precision, seasonally resolved into summer cooling (from 8117 to 7929 BP) and cold dry winters (8089-8006 BP). Time spans for these studies show that climatic deterioration across Western Europe struck within the interval 8300 BP to 7950 BP (Fig. 7).

A comprehensive pollen approach to temperature reconstruction in Europe, undertaken by Davis *et al.* (2003) places these findings in broader context (Fig. 9). In this vegetational study, surface air temperatures were assigned to 93 tree, shrub and herb taxa using Plant Functional Type analysis. Using over 2000 radiocarbon-dated pollen sequences, the mean annual, mean coldest and mean warmest monthly temperatures were then calculated for the complete Holocene, with a time resolution of 100 years. Postglacial recovery finds clear expression in both winter and summer curves, with the latter rising to an attenuated peak at 6000 BP (the thermal maximum). The gap between summer and winter curves closes gradually, showing a narrowing of seasonal temperature range, and thus a move from the more extreme continental conditions of the Early Holocene towards more oceanic moderation in the Middle Holocene. Cooling periods are recognised at several points: 11.5 ka, 9.4-9.0 ka, 8.5 ka, 5.7 ka and 0.5 ka BP. Three of these events match those already identified within the GISP2 record (Fig. 2), but the 8.2 ka BP event makes a slightly early appearance. An apparent mismatch like this might correspond to the earlier Rasmussen chronology rather than the Thomas equivalent (Fig. 7).

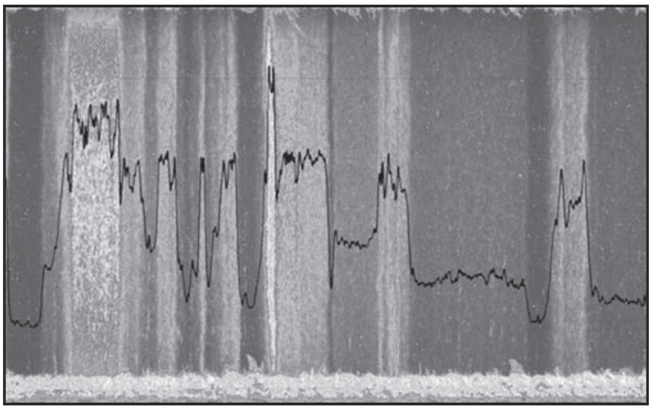

Figure 8. *Ice layering in core from the North Greenland Ice Core Project (NGRIP) showing annual banding from about 1800 m depth (about 20,000 years old). The black trace shows variations in light intensity measured by a line scanner (courtesy of Søren Wedel Nielsen, Texas A & M University).*

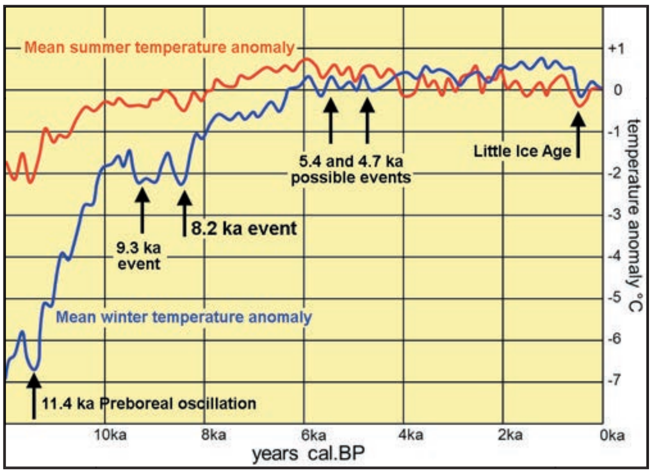

Figure 9. *Holocene temperature reconstruction for central western Europe (after Davis et al., 2003).*

Northern hemisphere reach

In the Mediterranean region the Early Holocene warm humid optimum is widely recognised in Sapropel S1 in numerous marine cores. Climatic deterioration at around 8.2 ka BP is observed in a marker horizon within S1 and is particularly well-preserved in the Aegean and Adriatic Seas (Rohling *et al.* 1997; Marino *et al.* 2009). Another key location is Tenaghi Philippon (Fig. 3), where a well-documented pollen sequence confirms cold dry conditions coincident with the mid-S1 interval (Pross *et al.* 2009; Peyron *et al.* 2011). Evidence within the wider Mediterranean basin is reviewed by Jalut *et al.* (2009), and links to the Middle East are discussed by Rohling and Palikë (2005). Farther afield, Jin *et al.* (2007) critically examine the 8.2 ka BP record in the Far East.

Aridity or humidity?

What was the hydrological response to the 8.2 ka BP anomaly? Clear expression of drought is undeniable in the Greenland ice cores (Alley *et al.*, 1997; Thomas *et al.*, 2007), and model simulations (Wiersma and Renssen, 2006; LeGrande *et al.*, 2008) point to general drying across the whole of the North Atlantic region and into the Mediterranean. In western Europe, the

***Figure 10**. The frozen River Thames in 1677 during the Little Ice Age; a painting by artist unknown, now in the Museum of London. These conditions give some hint as to the severity of cold aridity and the inevitable environmental crisis that struck Britain as the 8.2 ka event during the Later Mesolithic.*

impressive Holzmaar record clearly registers drier conditions in both summer and winter. Cold aridity in the broader region around the North Atlantic is inferred from reactivated aeolian sediments (sand dunes, cover sands and loess), identified and luminescence-dated to around 8200 BP at several locations: Michigan and Ohio (USA), Britain, Finland, Denmark, Netherlands, Germany, Spain, Portugal and the Canary Islands.

Not all studies agree with this interpretation, however. A shift to *wetter* conditions, for example, has been proposed for the 8.2 ka BP event in Britain (Macklin and Lewin 2003; Vincent *et al*. 2011), in Sweden (Seppa *et al*. 2005; Snowball *et al*. 2010) and in the Alps (Spötl *et al*. 2010). How do we account for these conflicting views? Dating uncertainties may be involved, while coarse time resolution can sometimes fail to detect short-term (decadal) oscillations. Palaeoclimatic interpretation of $\delta^{18}O$ proxies (in lake carbonates and speleothems, for example) is not always straightforward (Frisia *et al*. 2006; Spötl *et al*. 2010). In Norway, a period of significant glacial advance (the Finse event) occurs at 8200 BP, but this can be interpreted in terms of either increased winter snowfall or cooler summers with reduced ablation (Nesje *et al*. 2006).

Researchers increasingly recognise that answers must be sought at the detailed seasonal level. Hammarlund *et al*. (2005), for example, envisage strong seasonality in the Scandinavian examples, with dry cold winters alternating with cool (but more humid) summers. Another approach sees the 8.2 ka BP downturn expressing itself in a variety of different regional climates; one size may not fit all. This might seem a rather fail-safe, non-falsifiable working hypothesis, and it is suggested that a concept of cold aridity would provide a more consistent and workable framework. Further well-dated high-resolution investigations are clearly needed.

Some commentators have drawn a parallel with the Little Ice Age (Fig. 10). As far as it goes, this is a helpful analogue for understanding blocking anticyclone drought, but there are important differences. The Little Ice Age in all probability was driven by reduction in solar radiation alone. In contrast, the 8.2 ka BP event was more complex; it was a unique event in the Holocene, unlikely ever to be repeated. The temperature reversal at 8.2 ka BP was far greater than the Little Ice Age downturn, suggesting that environmental conditions in Europe were considerably worse at that time (Fig. 2).

Will history repeat itself?

In a word, no. But this has not prevented some sections of the media from peddling an alarmist message. In the late 1990s, emerging data from the Greenland ice cores and Atlantic marine cores popularised the concept of rapid climate change. Freshening of North Atlantic waters by global warming of the Greenland ice sheet could, it was said, theoretically shut down the Atlantic conveyor, plunging Western Europe into a glacial freeze within a decade or two. Following an IPCC report in 2001, predicting the possibility of imminent Atlantic conveyor shutdown, the New York Times ran an editorial in 2002 entitled “The Heat Before the Cold”, and the BBC screened a Horizon documentary on “The Big Chill” in November 2003. These voices lent credibility to a provisional study (Bryden *et al*. 2005) suggesting a 30% reduction in MOC between 1957 and 2004.

Picked up by the more sensational tabloid press, the story grew, fuelled by further speculation as portrayed in the 2004 disaster movie “The Day after Tomorrow” (which The Guardian described as a great movie but lousy science), and Al Gore’s “An Inconvenient Truth” in 2006. Meanwhile, theoretical modelling had already raised doubts. In 2004, the Lamont-Doherty Earth Observatory stated that in the event of a complete shutdown of the thermohaline circulation Europe might be cooled by 2-4°C, but the Gulf Stream itself, being partially wind-driven, would continue to be propelled onwards by the prevailing westerlies; Greenland ice-melt freshening would largely be confined to the Labrador Sea region. Later, Cunningham *et al*. (2007) published new data, revising the short-term figures of Bryden *et al.* (2005), to demonstrate that they were actually part of a natural cycle of variability. NASA have since published evidence (2010) confirming no significant slowing in the North Atlantic circulation since 1995, and certainly no change in circulation strength between 2002 and 2009.

An influential congressional report (Delworth *et al*. 2008) concludes that a 30% reduction in MOC strength is very probable during the 21st century, but that circulation collapse would be highly unlikely. It is emphatically not possible, in the authors' view, for global warming to cause an ice age. The report does warn, however, that global warming *of itself* will be responsible for MOC reduction, to which will be added an *uncertain* amount of freshening as a result of Arctic and Greenland ice-melt. The possibility therefore of complete MOC collapse beyond the end of the 21st century "cannot be entirely excluded". Thus the most likely scenario for Europe in this century will be a gradual slowdown (but not shutdown) of the North Atlantic Ocean circulation, but a repetition of the dramatic climate change reconstructed for the 8.2 ka BP event will not pose a threat in our lifetimes.

Acknowledgements

The author thanks the library staff at BGS Keyworth for kind assistance in locating some of the less accessible references in this literature review. Andy Howard, David Knight, Mark Bateman and Tony Waltham offered useful advice in its compilation, and Richard Hamblin is thanked for reviewing the draft and making helpful suggestions.

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On the record of ‘corals’ from the Late Triassic Arden Sandstone Formation, Western Park, Leicester

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Abstract: In 1849, John Plant reported “polypidoms of a coralline” from the “keuper sandstone” exposed in a railway cutting near Leicester. He proposed the name *Gorgonia Keuperi* for these structures, but this is a *nomen nudum*. Subsequent authors have consistently questioned the organic origin of ‘*Gorgonia Keuperi*’, or considered it to be an ichnofossil, but it has never been illustrated. Museum specimens labelled ‘*Gorgonia Keuperi*’ have been found to contain a number of ichnofossils, amongst which the commonly occurring *Planolites montanus* is considered most likely to be the inspiration for what John Plant termed ‘*Gorgonia*’.

Following the review of the distribution of corals in British Jurassic deposits from the *planorbis* Zone (Hettangian, Lias) upwards (Negus, 1983), the first author has been compiling records of corals from British Triassic deposits to complement that account. Swift (1999) reviewed occurrences of corals in the Penarth Group, of latest Triassic (Rhaetian) age. However, structures interpreted as “polypidoms of a coralline” had been reported from an older unit by John Plant at the Birmingham meeting of the British Association for the Advancement of Science in September 1849 (Plant, 1850). Plant proposed the name *Gorgonia Keuperi* for these remains which he recovered from the “keuper sandstone” near Leicester. This is, however, a *nomen nudum*, a name that is unacceptable; a holotype was not designated, formal diagnosis and description were not given, and no illustration was provided. Subsequent workers have consistently questioned the nature of ‘*Gorgonia Keuperi*’, with many doubting that it had an organic origin, but none has described or illustrated the material. The purpose of this contribution is to rectify these shortcomings and formally establish the nature and origin of this material.

Location and stratigraphy

John Plant obtained his specimens from the “keuper sandstone” exposed in a cutting on the “Leicester and Swannington” railway, at Shoulder of Mutton Hill (SK556042) in the western suburbs of Leicester (Fig. 1). This unit was subsequently termed ‘Upper Keuper Sandstone’ (James Plant, 1856; Bosworth, 1912), ‘Dane Hills Sandstone Group’ (Horwood, 1913) and ‘Dane Hills Sandstone Member’ (Warrington et al., 1980); it is now the Arden Sandstone Formation, within the Mercia Mudstone Group (Howard *et al*., 2008). Carney *et al*. (2009) stated, incorrectly, that it was named the ‘Hollygate Skerry Member’ by Warrington *et al*. (1980), and used ‘Hollygate Sandstone Member’, a modification of that term proposed by Charsley *et al*. (1990). The main outcrops of this formation are in Warwickshire, Worcestershire and Gloucestershire, where Murchison and Strickland (1840) recognised it as a sandstone unit within the ‘Red or Saliferous Marls’. James Plant (brother of John) considered this to be “the same formation” as that at Leicester, described by him (Plant, 1856), and later by Browne (1893), Fox-Strangways (1903), Bosworth (1912), Horwood (1913), and Carney *et al*. (2009). The formation also includes the units formerly known as the North Curry Sandstone and Weston Mouth Sandstone members that crop out in Somerset and on the southeast Devon coast respectively (Howard *et al*., 2008).

The Arden Sandstone Formation is a unique and widespread facies within the Mercia Mudstone Group (Warrington and Ivimey-Cook, 1992; Hounslow and Ruffell, 2006) and is relatively fossiliferous. At Leicester it has yielded ichnofossils of invertebrate and vertebrate origin, poorly preserved plant remains, and a macrofauna that includes conchostracan crustaceans and remains of fish and other vertebrates (Plant 1856; Browne, 1893; Horwood, 1908, 1913, 1916; Carney *et al*., 2009). Elsewhere in England, ichnofossils of invertebrate and vertebrate origin, miospores, a macroflora dominated by remains of conifers, and a macrofauna that includes bivalves, conchostracans and remains of fish and other vertebrates, have been recorded (Horwood, 1909; Clarke, 1965; Warrington, 1970, 1971, 1985; Fisher, 1972, 1985; Williams and Whittaker, 1974; Jeans, 1978; Warrington and Williams, 1984; Ruffell and Warrington, 1988; Old *et al*., 1991; Warrington and Ivimey-Cook, 1992; Barclay *et al*., 1997; Powell *et al*., 2000; Benton *et al*., 2002;

***Figure 1**. Arden Sandstone Formation in the railway cutting at Shoulder of Mutton Hill, Western Park, Leicester (for other illustrations of the unit in this area, see Browne, 1893, pl.1; Bosworth, 1912, fig.38; Carney et al., 2009, pl.12).*

Hounslow and Ruffell, 2006; Radley, 2006; Radley and Pollard, 2006; Porter and Gallois, 2008; and references cited therein). The miospores consist largely of pollen and are indicative of a Tuvalian (late Carnian, early Late Triassic) age (Fisher, 1985; Warrington, in Old *et al.*, 1991, Barclay *et al.*, 1997, and Powell *et al.*, 2000).

Previous work

The fossils first reported from the "keuper sandstone" in Leicester by John Plant (1850) included, in "bands of fine marl" between "gray shaly sandstones", bodies that he interpreted as "the polypidoms of a coralline" and described as occurring "in great profusion on the surfaces of nearly every band….. The polypidoms lie confusedly and in all instances occur as siliceous casts, the delicate organization of the cells being obliterated.". John Plant suggested the name *Gorgonia Keuperi* for these "fossil markings". His brother, James, made a contribution on the same beds, without reference to '*Gorgonia Keuperi*' but noted the presence of "Cololitic remains of Annelids, and casts of their tubes." (Plant, 1856: 373).

Browne (1893) noted that some of John Plant's specimens had been purchased by the Leicester Museum but that it was "exceedingly doubtful if they are organic.". However, he listed (on p.223), under Cœlenterata, Actinozoa, "*Gorgonia Keuperi*" (Plant) and "Polypidoms of coralline" from the "Upper Keuper Sandstones", citing Plant (1850) and Plant (1856).

Fox-Strangways (1903, 15) noted, with regard to possible plant remains from the "Upper Keuper" or "Dane Hills" Sandstone, that "…it is doubtful if some of them are organic. The same may be said of the doubtful coral *Gorgonia keuperi*, discovered by Mr John Plant, which Mr Browne does not consider to be organic.". Under Cœlenterata (Actinozoa), Fox-Strangways (1903, 96) listed "GORGONIA KEUPERI; Plant", from the "Keuper Sandstone" as "Probably not organic.".

Figure 2*. Upper (LEICT G154.1893.1):* Planolites montanus *(fine, criss-crossing burrows),* Treptichnus *isp. (ziz-zag or 'feather stitch' burrows) and* Ancorichnus [Biformites] insolutus *(short, straight, horizontal burrows with 'beading' or transverse packed infill in one or two rows, i.e. median groove). Lower (LEICT G154.1893.2):* Treptichnus pollardi *(large zig-zag burrow of three elements with enlargement at one end; also smaller examples); some small* Planolites montanus *burrows.*

Horwood (1908) tabulated the flora and fauna of the 'Keuper' in Leicestershire. With regard to *Gorgonia*, he noted (p.307) that "This *nomen nudum* was invented in 1849 for specimens which are probably nothing more than inorganic casts of tracks and galleries, the work of Worms or Crustacea.", and made the following observations on specimens in the Leicester Museum:

PLANTAE

Incertae sedis:

1893/155 - "Stem fragments" – "labelled casts of *Gorgonia* or Fucoids, but certainly neither."

1893/156 - "(Under *Echinostachys oblongus* Brong.)" – "The specimen …. exhibits no definite characters, and is associated with worm-tracks."

INVERTEBRATA

Annelida or Crustacea - "Cololitic remains of Annelida …. and casts of their tubes"

1893/154 – "(labelled *Gorgonia keuperi*."

1893/156 – "('casts of *Gorgonia* or *Echinostachys oblongus*')"… the latter "in so far as *Echinostachys* is concerned, may be partly referable to some plant; but the *Gorgonia* is only, like the other specimens, the work of worms or crustacea. No.1893/155, *supra*, may also be partly referable to the same agency."

1893/161 – "casts of probable worm-tracks or Fucoids."

According to Horwood (1908: 312), Seward (1904: 8) compared a specimen "named *Gorgonia keuperi*, but exhibited in the Fossil Plant Gallery" (in the Natural History Museum, London), with others, "to probably remains of *Voltzia.*". Seward had noted this specimen (BM 24, 190; Horwood, 1908: 307) under the heading of 'Indeterminable Remains', some of which he considered "are no doubt fragments of Coniferous plants (*Voltzia*?)" but had described it as "Half-relief tracks or castings, labelled "*Gorgonia Keuperi*", from the Keuper Sandstone of Leicester. Presented by James Plant, Esq., 1849.". This specimen (NHM PB OR 24190; Fig. 6) is reviewed below.

Despite their suggestions regarding the nature of these specimens, none of the above authors provided an illustration or adequate description. The opportunity is therefore taken to rectify this situation and to clarify the nature of the material.

Description of the specimens

The authors have undertaken a review of John Plant's material, curated in the Leicester Museum and in the Natural History Museum, London, and confirm that none is of coralline origin. The following interpretations and identifications are by the second author.

***Figure** 3. (LEICT G161.1893):* Planolites montanus *(dominant; two size groups, short irregular horizontal burrows c.1-2mm and <1mm diameter);* Treptichnus pollardi *? (rare; zig-zag burrows with short straight elements);* Ancorichnus [Biformites] insolutus *? (rare; sand-filled burrows with a faint median groove and single or double beaded infill). There may also be a drag mark (?) crossing the specimen.*

New Walk Museum, Leicester

Specimens LEICT G154.1893.1, G154.1893.2 and G161.1893 are curated as "'reference' specimens of Triassic ichnofossils *Gorgonia keuperi*, possibly annelid castings or trails".

LEICT G154.1893.1 (Fig. 2, upper). Lower surface: curved channel-like form with *Planolites montanus* Richter 1937 (background of fine, criss-crossing burrows of several sizes), *Treptichnus* isp. (several clear zig-zag or 'feather stitch' burrows), *Ancorichnus* [*Biformites*] *insolutus* (Linck) 1949 (short, straight, horizontal burrows with 'beading' or transverse packed infill in one or two rows, i.e. median groove). Upper surface shows mud-draped interference ripples.

LEICT G154.1893.2 (Fig. 2, lower). Small slab of grey sandstone. *Treptichnus pollardi* Buatois and Mangano 1993 (large zig-zag burrow of three elements with enlargement at one end; also smaller examples); *Planolites montanus* – a few small burrows.

LEICT G161.1893 (Fig. 3). Fine, grey-green sandstone with mud-coated upper and lower surfaces; diverse small sand-filled burrows on the latter. *Planolites montanus* (dominant; two size groups, short irregular, horizontal burrows c.1-2mm and <1mm diameter); *Treptichnus pollardi* ? (rare; zig-zag burrows with alternating short straight elements); *Ancorichnus* [*Biformites*] *insolutus* ? [rare; sand-filled burrows with a faint median groove and single or double beaded infill, described as *Biformites* from the German Schilfsandstein by Linck (1949) and reassigned by Seilacher (2007, 94, pl. 32)]. There may also be a drag mark (?) crossing the specimen.

***Figure** 4. (LEICT G149.1893):* Planolites montanus*, and a drag mark (?), possibly produced by a broken* Equisetites.

LEICT G149.1893 (Fig. 4). Appears to show *Planolites montanus* and what might be interpreted as a cast of a drag mark, perhaps produced by a broken *Equisetites*, that predates the burrows.

LEICT G155.1893 (not illustrated)**.** Small triangular specimen with a few *Planolites montanus* burrows and two divergent lobed moulds (arthropod resting traces?).

LEICT G156.1893 (Fig. 5). "*Gorgonia* or *Echinostachys oblongus*". Burrows predominantly *Planolites montanus* but also a larger cylindrical sand-filled burrow, 14mm in diameter and possibly with a short lateral branch and faint lateral scratch marks; if correct, this could be *Spongeliomorpha* [*Steinichnus*] *carlsbergi* Bromley and Asgaard 1979 which is also known from late Triassic fluvial sandstones of East Greenland (Bromley and Asgaard, 1979).

Natural History Museum, London

NHM PB OR 24190 (Fig. 6). Under-surface of a grey-green sandstone showing randomly oriented horizontal burrows preserved in semi-relief. *Planolites montanus*

***Figure** 5. (LEICT G156.1893):* Planolites montanus *(dominant) and a larger sand-filled burrow that may be* Spongeliomorpha [Steinichnus] carlsbergi.

***Figure 6**. (NHM PB OR 24190):* Planolites montanus *(dominant) and rarer* Ancorichnus [Biformites] insolutus *? (photo: NHM London).*

(abundant, short sand-filled burrows) and *Ancorichnus* [*Biformites*] *insolutus* ? (rare burrows with faint central groove or beaded infill).

Discussion

The identification by John Plant, in 1849, of structures in the "keuper sandstone" near Leicester as "polypidoms of a coralline" (Plant, 1850) appears to have been conditioned by comparison with the common branching structure of a colony of polyps of a sea-fan. He therefore referred the "polypidoms" to the recent genus *Gorgonia* Linnaeus 1783, and created the invalid species '*Gorgonia Keuperi*'. Citations of fossil specimens of *Gorgonia* are erroneous (Bayer, 1956) and in the present instance clearly relate to abundant *Planolites montanus* burrows. These conclusions confirm previous workers' doubts about the nature of these specimens as body fossils.

Reference to possible plant remains (*Echinostachys oblongus*) on specimen LEICT G156.1893 (Horwood, 1908) may relate to the larger cylindrical burrow with the lateral branch on that specimen (Fig. 5*)*, identified above as possibly *Spongeliomorpha* [*Steinichnus*] *carlsbergi*. Grauvogel-Stamm (1978) noted that, up to that time, the genus *Echinostachys*, with the type species *E. oblonga*, from the Grès à Voltzia in the Bas-Rhein area of France (Brongniart, 1828), had been considered *incertae sedis*. However, Grauvogel-Stamm (1978: 70) interpreted *E. oblonga* as a male reproductive organ (with *in situ* microspores), and placed it in the new combination *Schizoneura-Echinostachys paradoxa* (Schimper & Mougeot) Grauvogel-Stamm, 1978 (Kustatscher *et al*., 2007).

Facies considerations

Units now united in the Arden Sandstone Formation in England (Howard *et al*., 2008) have been noted as containing *Planolites* at localities ranging from Devon to Warwickshire (Warrington and Williams, 1984; Ruffell and Warrington, 1988; Old *et al*., 1991; Warrington and Ivimey-Cook, 1992; Barclay *et al*., 1997; Porter and Gallois, 2008). The association of *Planolites montanus* and *Treptichnus*, first noted by the second author in the Arden Sandstone Formation at Rowington, Warwickshire, in 1979, has been confirmed by Porter and Gallois (2008) who used it as the basis for a Planolites ichnofabric (Pl) which they interpreted as the result of short-lived opportunistic colonisation by an infaunal deposit feeding community, mostly in lacustrine environments, but also at lake margins and in minor channels and floodplains. These considerations alone would preclude the possibility of corals occurring in the Arden Sandstone Formation.

Conclusions

Specimens in Leicester Museum curated as "*Gorgonia keuperi*" (Figs 2, 3) are clearly ichnofossils, predominantly *Planolites montanus*, but including *Treptichnus pollardi* and other ichnotaxa. *Planolites montanus* is, on account of the convolute and densely intertwining nature of the tubes that constitute this ichnofossil, considered most likely to have provided the inspiration for what John Plant termed '*Gorgonia*', and his interpretation of this as a coral may reasonably be attributed to a perceived similarity with the gorgonian sea fans (Anthozoa, Octocorallia, Alcyonacea).

Acknowledgements

Mark Evans, Senior Curator, kindly facilitated examination and photography of John Plant's specimens in the Leicester Museum collection and commented on a draft of this account. Dr M. Munt, Dr L. Stevens and Ms J. Darrell, all at the Natural History Museum in London, are thanked for locating the specimen noted by Horwood as displayed in the Fossil Plant gallery, for providing the illustration of that specimen, and for helpful comments on a draft of the manuscript. Dr E. Kustatscher, at the Naturmuseum Südtirol in Bolzano, kindly advised on the status of *Echinostachys oblonga*.

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The occurrence of calcium phosphate in the Mesozoic and Tertiary of Eastern England

Albert Horton

Abstract: Phosphate is a minor component of Mesozoic and Tertiary formations. It occurs widely scattered as nodules in argillaceous sediments, but is commonly concentrated in pebble beds and may be found replacing fossils. Phosphatic animal remains are rare and commonly occur immediately above major discontinuities, and fossilised animal faeces (coprolites) are extremely rare. Phosphatic pisoliths occur at only one horizon.

In Eastern England calcium phosphate occurs as coprolites, bones, fossil replacements, ill-defined impregnations, nodules, pebbles, pisoliths and hardgrounds in Mesozoic and Tertiary strata. Many geologists (*eg*. Horton *et al*., 1974, p.35) have been guilty of imprecise use of these terms. Using local examples it is possible to obtain a clear understanding of the diverse origins of these deposits.

Phosphorus occurs as a minor element in igneous rocks. Weathering and erosion result in transfer of the element within detrital grains and in solution. In marine environments, the phosphorus may be concentrated by physical, chemical and biological processes, 'precipitated' as calcium phosphate nodules, bones and coprolites and subsequently reworked as pebbles.

Coprolites

Coprolites are trace fossils made up of faecal material. Duffin (2009) records how in the 18th century a group of ornamented stones from the Chalk were thought to be cones and fruits of trees. It was Buckland (1822, 1823) who, on the basis of his work on Kirkdale Cave, recognised fossil hyaena faeces. With others, he found faeces in the basal beds of the Lias, the basal Rhaetic Bone Bed and the basal conglomerate of the Carboniferous Limestone. He concluded that the Cretaceous fossils were also of faecal origin and should be referred to as *Copros iuloides*. Buckland's final proposal was to "include them under the generic name of Coprolite", from the Greek, cous = dung, lithos = stone (Duffin, 2009).

The early 19th-century fossil collectors of Lyme Regis found unusual ornamented " Bezoar stones" from the Lower Lias (Buckland, 1829). These were recognised as faeces by Buckland (1836) who described them as occurring at some levels as 'being so abundant that they lie like … potatoes scattered on the ground'. This contrasts with the experience of the author and colleagues who have spent careers studying Mesozoic clay formations in exposures and borehole sequences without finding a coprolite. The author's only possible candidate is a faecal pellet from the Lower Lias. Such pellets are small, fawn-coloured cylinders, 1-2 mm in diameter and 4-5 mm long. Although fragile, they have linear ridges that are suggestive of extrusion, and they occur in association with scattered simple ornamented plates, possibly of crustacean origin.

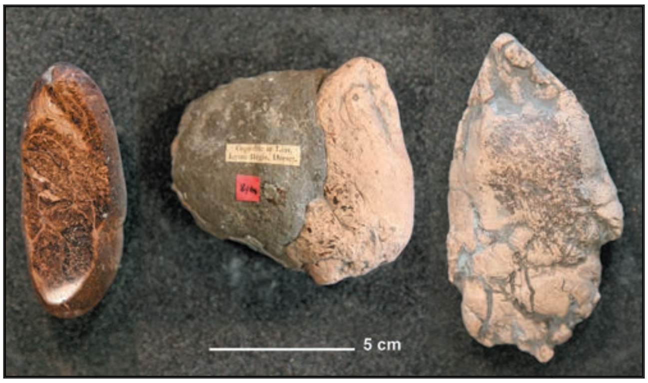

Figure 1. *Coprolites from the basal Scunthorpe Mudstone Formation, Lias Group at Lyme Regis, Dorset (all photo courtesy of British Geological Survey).*

The success of the early coprolite collectors may reflect the coprolites' original large numbers and their subsequent concentration by selective marine erosion with wave sorting of the dense material (Figs. 1 and 2). In ancient brick pits, clay was removed in layers, thereby exposing bedding planes and their contents much more accessibly than in the few pits working today with mechanical excavation and vertical sections. Ford and O'Connor (2009) conclude that 'most coprolites come from the larger marine reptiles or fish which fed on their smaller brethren and concentrated phosphate in their faeces'.

In the mid-19th century, phosphate was worked commercially from several horizons. These were

Figure 2. *Small (fish) coprolites from Lyme Regis.*

described informally as ‘coprolite beds’ and ‘coprolite workings’, which are misnomers since the beds contain few, if any, coprolites. The error started with Henslow (1846) who, although writing on concretions in the Red Crag at Felixstowe, was inclined to describe them as ‘water-worn pebbles’ but wrongly concluded that they were coprolites. The error was recognised by Charlesworth (1868, p.577): ‘ a mistake, but one, perhaps, of the happiest mistakes ever made by a man of science; for had not Professor Henslow believed these stones to be coprolites (fossil dung) he would never have had them analysed, and the phosphatic nature and consequent agricultural value of these stones might possibly for centuries to come remain unknown’.

Bones

Phosphatic animal remains, including those of dinosaurs, mammals and fish (bones and teeth), are found in the lag gravels associated with major disconformities. Most were derived from the erosion of older sediments, but in the case of the youngest strata some may have been penecontemporaneous

Nodules

Nodules may be irregular, spheroidal, or ellipsoidal and are commonly composed of calcite, siderite, silica, gypsum or phosphate. Concretions have a similar origin, but are larger and most commonly calcareous. Nodules are autocthonous, in that they are enclosed in the sediment within which they formed.

Unconsolidated clay-rich sediment may be described as a chemical soup. Phosphorus may occur within decaying marine organisms, within mineral grains, loosely bound within the structure of clay minerals or as phosphate ions in solution. During diagenesis, compaction of the mud mobilizes the pore-water which becomes increasingly enriched with minerals. These react and attempt to reach equilibrium in the evolving chemical environment. Variation in chemical composition, perhaps enhanced by the presence of decaying organic matter, creates chemical gradients with migration of phosphate-rich solutions and the precipitation of calcium phosphate at nodal points, commonly organic detritus and shells.

Phosphatic nodules are most common in marine Mesozoic and Tertiary mudstones. They may be isolated and scattered throughout the sediment, but are commonly located on specific bedding planes. The latter may be sufficiently abundant to constitute ‘a bed’. The paramount factor is that the nodules remain *in situ*, in their position of growth. Many nodules are structureless, showing no evidence of their initial trigger to growth, whereas others may partially enclose or totally replace organisms.

Pebbles

These are fragments, 2-64 mm in diameter, which have been separated from their source rock, abraded and rounded during transport to a new location. Pebbles are allocthonous, i.e. separated in time and space from their source rock. Generally the term is applied to hard rock fragments derived from strongly indurated strata. It can also be applied to debris of weakly consolidated sediments in which diagenesis is well advanced and nodules have already formed. Thus eroded nodules become pebbles with minimal abrasion and transportation.

Breaks in sedimentation within the Mesozoic range from geologically short-lived hiati, between beds within formations, to increasingly longer gaps between formations, groups and systems. The breaks may be marked by a burrowed surface, a lag deposit (gravel), an inter-formational conglomerate, or a major erosion surface overlain by far-travelled exotic pebbles. All types occur within England, and phosphatic pebbles may be a significant component in them. Phosphatic pebbles have been described from a number of horizons.

Rhythmic sedimentation is common in Mesozoic mudstones, and is particularly well developed in the Gault (Gallois and Morter, 1992). An idealized Gault rhythm starts with a period of increased current activity causing erosion of the underlying bed, and then the development of an inter-burrowed basal surface (Fig. 3). This may be glauconitised or phosphatised, and is overlain by a silty, shelly, pebbly mudstone containing

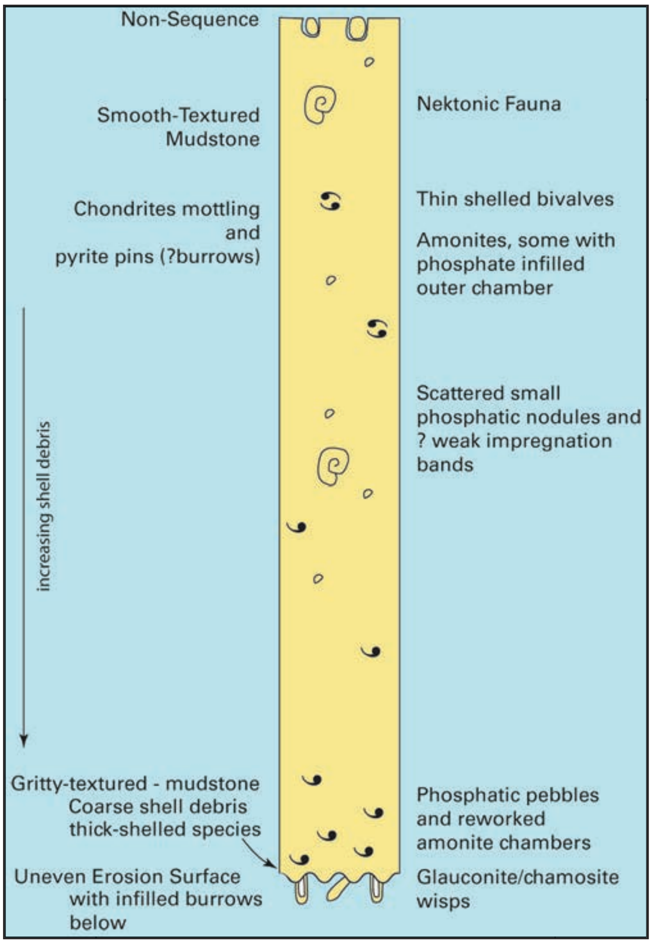

***Figure 3**. A typical sedimentary rhythm that is present in many Mesozoic marine mudstone sequences (after Gallois and Morter, 1982).*

waterworn phosphatic pebbles, some with encrusting organisms, and others with superficial micro-borings, exhumed burrow-fills, derived belemnites, oysters, etc.. In time, current activity declined, the silt content decreased upward, fossils were preserved and phosphate nodules were precipitated within the clay sediment. These rhythms are only 1-2 m thick. Each started when the mudstone was partly consolidated, and any increase in current activity caused erosion, downcutting and winnowing of the newly formed nodules and thicker shells. The phosphatic nodules were eroded with minimal abrasion, and further reworking may have enhanced the phosphatisation. The presence of encrusting organisms and microborings confirm the conversion of nodules to pebbles.

Hardgrounds

These are indurated surfaces developed within recently lithified sediments, commonly limestones, during subsequent periods of very limited sedimentation and reworking. These phosphatic impregnations have irregular forms and some have a complex history of formation. They occur in the Chalk Rock. Three 'indurated phosphatic mudstone' horizons have been recognised within bed 15 of the standard Upper Gault sequence in the Arlesey borehole, Bedfordshire (Woods *et al*., 1995). Further details are not available and specimens were not retained.

Pisoliths

Calcareous ooliths and pisoliths are generally deposited as calcite in a high energy marine environment. These sediments are commonly converted to limestones which may, very rarely, be subsequently altered to phosphatic material. An extremely unusual example of 'free' phosphatic pisoliths occurs in the local Whitby Mudstone Formation (Upper Lias).

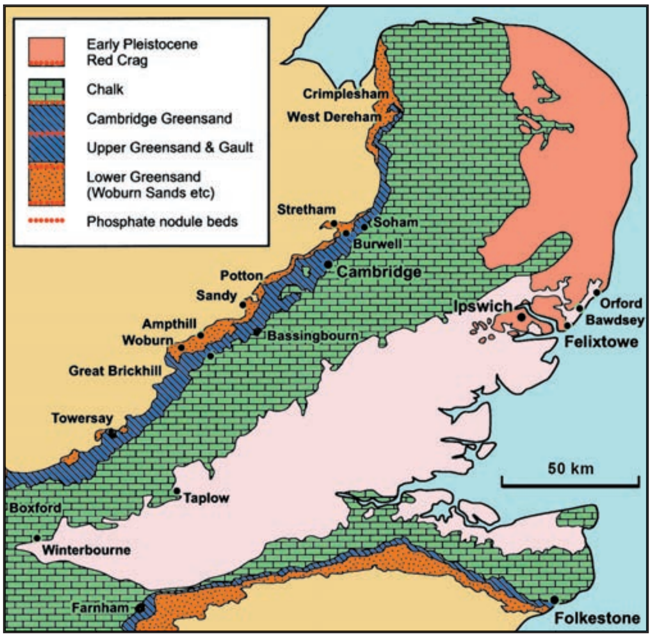

Figure 4*. Some of the main sites of the former extraction of 'coprolites' (after Ford and O'Connor, 2009).*

Age	Formation	
Neogene	Red Crag	E*
	Coralline Crag	E
Upper Cretaceous	Cambridge Greensand	E*
Lower Cretaceous	Upper Gault	E
	Lower Gault	E
	Woburn Sands	E
Upper Jurassic	Portland	E
	Kimmeridge Clay	
	Ampthill Clay	
	Corallian (Beckley Sand)	
Middle Jurassic	Northampton Sand	
Lower Jurassic	Whitby Mudstone	
	Marlstone Rock	
	Charmouth Mudstone	
	Scunthorpe Mudstone	

Figure 5*. Formations that contain significant amounts of phosphate. E = formation from which phosphate has been extracted; E* = major source of phosphate.*

Stratigraphic distribution

The various occurrences (Fig. 4) can be related to their depositional environments and then reviewed in stratigraphical order (Fig. 5).

Triassic

Penarth Group, Westbury Formation

The presence of coprolites in the 'Rhaetic Bone Bed' which occurs at or near the base of the Westbury Beds, has been known since the early 19th century (Buckland, 1829). Duffin (1979) has recognised five morphological types from the British exposures. Types with distinct geometric form, spiral patterns, or protruding bones are clearly identifiable. Others may vary in form and could be mistaken for spheroidal or mis-shapen nodules, phosphatic pebbles or phosphatised fossils.

Fish teeth have been described from the Westbury Formation at Barnstone (Sykes, 1979) and fossil vertebrates from the Newark area (Martill and Dawn, 1979). Resurvey of the Nottingham district proved several phosphate bearing horizons ('bone beds') in the Westbury Formation (Howard *et al*, 2008). A siliceous sandstone near the base contains coprolites and vertebrate remains. A bed at a higher level contains abundant fish and reptile remains, rolled phosphatised coprolites and quartz granules. Phosphatic pebbles and nodules occur in all beds.

Jurassic

Scunthorpe Mudstone Formation

This formation was formerly known as the lower part of the Lower Lias. The two youngest units, the Beckingham and Foston Members contain separate beds of 'calcareous nodules' and 'phosphatic nodules', with the phosphatic nodule beds occurring beneath locally persistent limestones (Brandon *et al*, 1990). The oldest underlies the Stubton Limestone, a ferruginous bioclastic limestone with limonitic ooliths and abraded and bored *Gryphaea*, and here contains minutely bored small phosphatic pebbles. Bored phosphatic 'nodules' also occur below the Fenton Limestone, while those below the Highfield Limestone are associated with bored and reworked ammonites. The Highfield Limestone contains *Gryphaea*, some abraded and bored, and also reworked phosphatic pebbles. Although the phosphate is described as nodules, the evidence of boring and transportation suggests that some may be pebbles.

Charmouth Mudstone Formation

In the Melton Mowbray district, the basal Glebe Farm Bed is a thin ironstone with reworked phosphate and calcite mudstone nodules that rests on an erosional surface (Carney *et al.*, 2002).

A borehole investigation for an underground gas storage scheme at Chipping Norton proved both the Scunthorpe and Charmouth Mudstone Formations of the Lower Lias (Horton and Poole, 1971). Most of the mudstones were not cored, but geophysical logs revealed three marker horizons within the Charmouth Mudstone. These were arbitrarily named, in increasing age, as the 100, 85 and 70 markers. Cores taken at these horizons revealed that the 70 marker lies within the *Uptonia jamesoni* zone, the 85 within the *Tragophylloceras ibex* zone, and the 100 at the boundary of that zone with the *Prodactylioceras davoei* zone. The geophysical signatures resulted from limestones and marls within the predominantly clay sequence. The argillaceous strata showed evidence of rhythmic sedimentation, but this was less clear in the calcareous beds. The base of an ideal rhythm is defined by a pause in the sedimentation, sometime with erosion and U-shaped burrows (Fig. 3). This is overlain by coarse, shell-debris-rich mudstones and limestones with thick-shelled bivalves typical of deposition in a high-energy environment. Ferruginous and phosphatic nodules and pebbles were recorded, but none was analysed. The amount and grain-size of the shell debris decreases upward as the mudstones pass into smooth-textured mudstone with *Chondrites* mottling and immature bivalves.

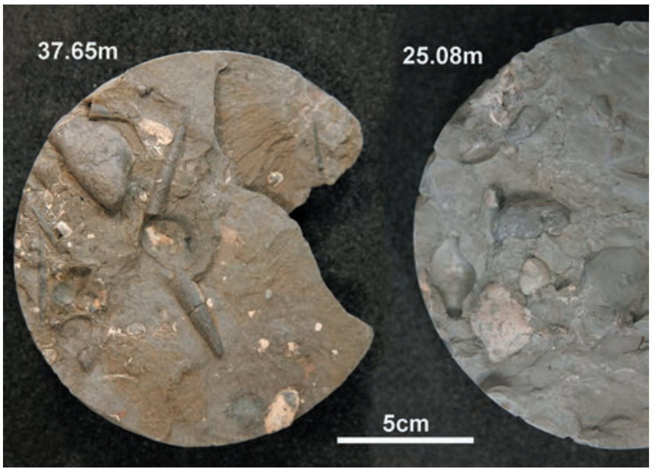

Figure 6. *Phosphatic pebbles with belemnites, bivalves, shell debris and chamosite silt, marking the base of two sedimentary rhythms within the Charmouth Formation at indicated depths in the Thorpe-by-Water Borehole, Rutland.*

The Charmouth Mudstone was proved in a series of cored boreholes, drilled on behalf of the British Geological Survey in the Buckingham-Huntingdonshire area. The youngest beds of the Charmouth Mudstone (*Prodactylioceras davoei* zone) consist of grey mudstone with a rhythmic pattern of sedimentation. The base of each rhythm is marked by a burrowed surface overlain by thin chamositic silt with black phosphatic pebbles, some of which were chambers of the zonal ammonite *P. davoei* (Fig. 6). This is overlain by smooth mudstone with scattered shells including ammonites. The calcitic shells of the latter were crushed during compaction except for the last body chamber which was sometimes infilled with phosphate. Sedimentation continued until a change in bottom conditions when a period of increased current activity resulted in erosion of the recently deposited clay, thereby revealing the nodular ammonite fragments. These suffered minimal abrasion during their transformation into pebbles and deposition at the base of the next rhythm. The Charmouth Mudstone passes up into the overlying Dyrham Silt Formation, and the base of the latter was drawn at the top of the last rhythm with a phosphatic *P.davoei* pebble.

Marlstone Rock Formation

Along its outcrop from Banbury to Lincolnshire, the base of the Marlstone Rock is locally marked by a conglomerate with discoidal pebbles, up to 80 mm diameter, of pale brown, phosphatic siltstone-mudstone (Fig. 7). These were derived from the underlying Dyrham Silt Formation, which is relatively soft, and may have been locally strengthened by phosphatisation during erosion. High density black phosphate pebbles have not been found.

Whitby Mudstone Formation

This formation (previously the Upper Lias) was well exposed during the construction of the Empingham Dam to impound Rutland Water, where it illustrates the diversity of phosphate deposition (Horton and

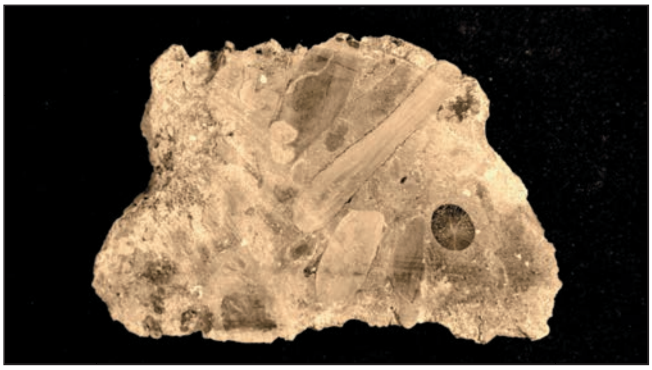

Figure *7. Basal conglomerate of the Marlstone Formation at depth 5.4 m in the BGS Thorpe-by-Water Borehole, Rutland; sawn vertical surface with dark belemnite platy phosphatised siltstone pebbles from the underlying Dyrham Formation.*

Coleman, 1977). The basal Fish Beds Member is a very thinly laminated mudstone, with bedding planes rich in immature *Posidonia* spat with phosphatic chitinous insect and fish remains. The top bed of the succeeding Cephalopod Limestone Member is the Pisolite Bed, a micritic limestone and marl. Within it, scattered large pisoliths were originally deposited as calcite and formed in a high energy environment (Fig. 8). They were replaced by phosphate, presumably in a quiet-water situation, and then transported and deposited with the calcareous micrite in which they now float. The micritic matrix is structureless with no evidence of bioturbation. The presence of an extremely small eroded fragment comprising phosphatic ooliths and phosphatic matrix indicates that in at least one (so far unique) area a second stage of phosphatisation preceeded final deposition (Fig. 9).

Phosphatic nodules are scattered in the overlying mudstone which also contains weakly impregnated phosphate beds, scattered nodules and a bed with many nodules, the ‘Smartie’ Nodule-Bed. Higher in the sequence the Ammonite Nodule Bed is a hard calcareous mudstone containing wisps of fine shell debris, calcareous nodules (up to 70 mm across) and ammonites, bivalves and belemnites, some of which are phosphatised. A hiatus at the base is marked by a bed of coarse shell-debris, which extends down in burrows into the underlying smooth-textured mudstone

The mudstones at the top of the Whitby Mudstone are slightly silty with scattered small phosphatic nodules. They contain evidence of a second hiatus with a major burrowed surface overlain by a thin lenticular conglomerate that passes laterally into silty shell-debris partings. Pebbles vary in size and shape, the more rounded are more highly phosphatic, and are probably reworked nodules (Fig. 10). Large irregular pebbles are phosphatised limestone concretions. The associated fossils include thick-shelled oysters, belemnites and rare rhynchonellids, set in a glauconitic pyritic sandy matrix. Some of the pebbles are bored, and parts of the top of the bed are encrusted with calcareous algae. This non-sequence and associated lag gravel has not been described for any other Upper Lias site. Despite daily examination and mapping of the ground beneath the proposed dam during its construction, not one coprolite was discovered (Horswill and Horton, 1976).

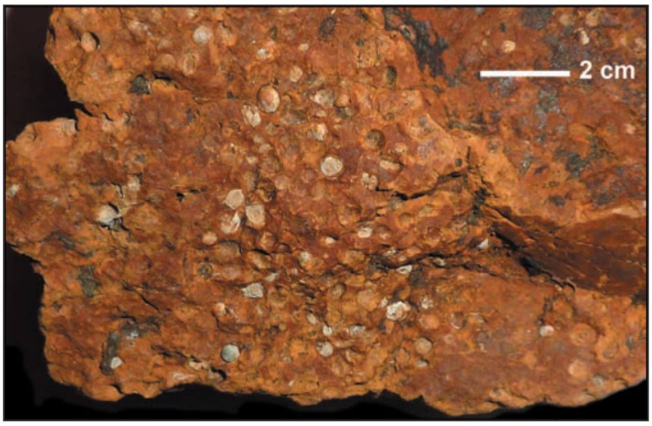

***Figure 8**. Pisolite Bed in the Cephalopod Limestones of the Whitby Mudstone at Holwell North Quarry, Melton Mowbray. Phosphatic pisoliths ‘float’ in weathered micritic matrix of the limestone.*

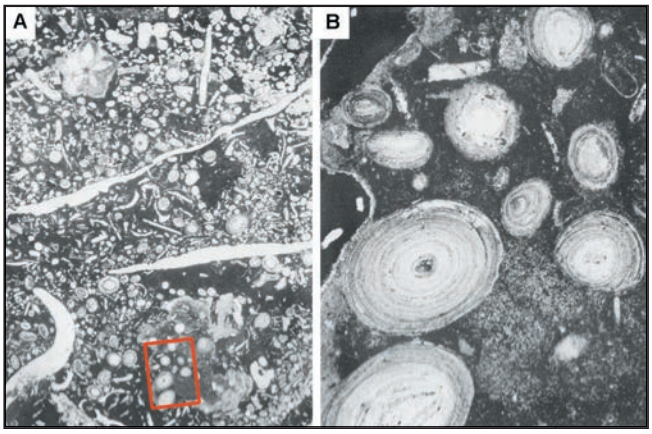

***Figure 9**. Photomicrographs of thin sections of ooids from the Cephalopod Limestones Member of the Whitby Mudstone, in the BGS Apley Barn Borehole, Witney, at a depth of 51.5m. A = shell-debris oolitic sideritic micritic limestone, with a pentacrinoid ossicle top left. B = 10x enlargement of the red box in A within a derived fragment of finely crystalline cellophane (phosphate) with unsorted phosphatic ooliths having concentric layers a few microns thick.*

Northampton Sands and Scissum Beds

The Northampton Sand Formation and its lateral equivalent in the Cotswolds rest disconformably upon the Whitby Mudstone Formation (formerly Upper Lias). The basal pebble bed contains phosphatised pebbles, some of which show shallow borings, and black phosphate pebbles. Because of its high phosphorus content, it was left as the floor beneath the ore-grade material of the Northampton Sand ironstone quarries. Although commonly much less than 30 cm thick, it provided a base for the rail track used by the wagons to transport the iron ore. The Whitby Formation was commonly exposed in shallow drainage ditches.

Oxford Clay Formation

Alan Dawn reported that he had collected coprolites from the Stewartby Member (formerly the Lower Oxford Clay) in brick pits near Peterborough. In his search for reptile skeletons he examined the abandoned steep quarry faces for protruding bones. A major mechanical excavation down from the ground surface to one such prospect was successful (Martill *et al*., 1979), wherein a final excavation by hand revealed a bedding plane with skeletons of reptiles and fishes and small coprolites up to 20 mm in diameter. These were associated with small rods, 1-2 mm in diameter and up to 5 mm long, that were similar to the probable faecal remains described herein from the Charmouth Mudstone Formation. Alan Dawn collected one large coprolite and many small specimens from the rain-washed weathered spoil heaps on the quarry floor.

Corallian Formation, Beckley Sand Member

Small rounded phosphate pebbles in association with chert and quartz have been recorded in thin, localised lag gravels near Oxford (Horton *et al*., 1995).

Ampthill Clay Formation

At least five phosphatic 'nodule' beds occur in the Ampthill Clay in the Wash area (Gallois and Cox, 1977). Each bed forms the base of a rhythm is defined by a basal, burrowed erosion surface. This is overlain by a gritty, shell-rich clay with thick-shelled oysters, commonly encrusted with serpulids, and rolled fossil fragments. The sequence continues progressively upward into smooth-textured mudstone. Each rhythm is thought to represent an increasing depth of water and progressively quieter bottom conditions.

The phosphatic nodule beds are said to contain 'phosphatic chips' and one contains 'phosphatised ammonite and bivalve debris', another 'rolled belemnites and oysters, the beds are shown to rest on intra-formational unconformities (Gallois and Cox, 1977). Given this evidence of erosion, it may be more appropriate to refer to the nodules as 'pebbles'. In the Thame district, the equivalent beds contain small rounded to angular phosphatic clasts, some of which are internal moulds of bivalves or ammonite body chambers (Horton *et al*., 1995).

Kimmeridge Clay Formation

In the Thame district, a phosphate pebble bed at the base of the Kimmeridge Clay cuts down to various levels in the topmost beds of the Ampthill Clay (Cox and Sumbler, 1991). The Lower Lydite Bed marks a second erosional event. This thin bed again contains phosphatised casts of bivalves and ammonite whorl chambers with sporadic small pebbles of lydite (black chert) and quartz. There is some evidence that the phosphatic clasts were phosphatised before erosion from *Pectinatus* zone sediments (Cox *et al*., 1990).

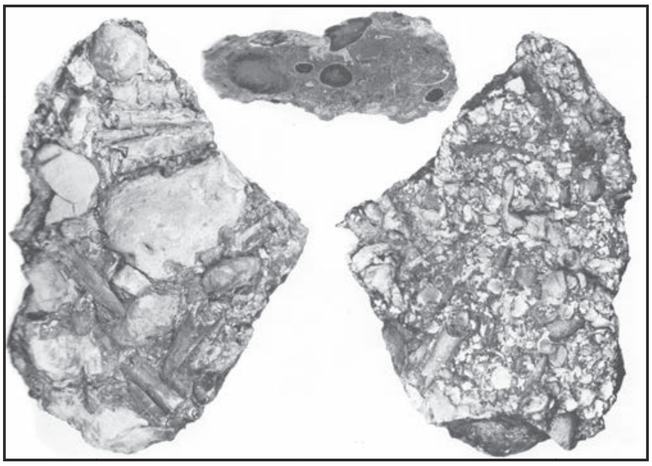

Figure 10*. Impersistant conglomerate in the upper part of the Whitby Mudstone Formation, at Empingham Dam site, Rutland Water. The upper surface (right) consists of shells, including belemnites and small pebbles, whereas the lower surface (left) includes large pebbles with borings and belemnites. The smaller fragment contains shell debris and phosphatised pebbles that have darker rims and enhanced radioactivity.*

Portland Formation

In the Thame district, the base of the Portland Formation is marked by an erosion surface (Horton *et al*., 1995), Commonly this is overlain by the Upper Lydite Beds, which are limestones characterised by small lydite pebbles associated with quartz and quartzite, and also rare black phosphate pebbles that include casts of ammonite whorl fragments.

Cretaceous

Lower Greensand, including Woburn Sands

In the Leighton Buzzard District the Lower Greensand comprises the thick Woburn Sands division and the thin, overlying Junction Beds. It rests unconformably on undivided West Walton and Ampthill Clay formations of Upper Jurassic age.

Phosphatic pebbles have been recorded in at least two levels within the Woburn Sands (Sheppard-Thorn *et al*.,1994). They were formerly extracted for fertilizer at localities between Little and Great Brickhill, Bedfordshire. Hereabouts a basal sandstone contained well-preserved, reworked phosphatic bivalves and brachiopods with whorl fragments (chambers) of pavlovid ammonites derived from the Jurassic Kimmeridge Clay. Higher in the Woburn Sands, an erosion surface locally cuts out 3 m of strata that overlie a major seam of Fuller's Earth. Above it a basal pebble and grit lag deposit includes dark lydite and quartz pebbles and also phosphatic ammonite fragments of Upper Jurassic provenance.

There was a break in sedimentation after the deposition of the Woburn Sands. Subsequently the sea transgressed a gently uneven surface of the Woburn Sands and deposited the Junction Beds, an extremely variable and laterally impersistent sequence of lithologies. They include the marine Shenley Limestone, which contains pockets of ironstone and passes laterally into glauconitic sandy marls with phosphatic nodules and ironstone fragments. These beds have not been exploited for phosphate; they are overlain by the Lower Gault.

In the Cambridge District the Woburn Sand facies is replaced by typical, marine, glaucontic Lower Greensand that overlies the Kimmeridge Clay non-sequentially. Between Westwick and Cottenham, northwest of Cambridge, 'the basal 1.2-1.5 m of the Lower Greensand comprises brown sand and clayey sand with phosphatic nodules, derived Jurassic ammonites, indigenous fossils, ironstone nodules and clay lumps with secondary calcite nodules' (Worssam and Taylor, 1969). This bed was worked for phosphate.

To the northeast, near Upware, Keeping (1868) described an unlocated excavation that showed 2.56 m of Gault Clay with 0.13 m of phosphate nodule bed above the base. Keeping's diagram lacks a scale but shows the Gault overlying Lower Greensand that rests on Kimmeridge Clay. Worssam and Taylor (1969, p.31) reinterpreted the sequence to show about 0.45 m of red and yellow sand, overlying an Upper Nodule Bed about 0.3 m thick, a pebbly sand with pale phosphate of lime, pebbles of chert etc., and many well preserved brachiopods. This rests on 0.45 m of red and yellow loose sand, which in turn overlies the Lower Nodule Bed, also about 0.3 m thick, which is a pebbly sand and conglomerate with nodules of phosphate of lime, pebbles of chert, etc, with many well preserved molluscs, overlying Kimmeridge Clay. It is probable that all three 'phosphatic nodule' beds were exploited. Keeping (1883) noted that the fauna of the Lower Bed included bones and teeth of reptiles and fishes, brachiopods, sponges, bryozoa, a few echinoids, annelids and a rich assemblage of molluscs. Worssam and Taylor (1969) described the bed as a condensed deposit, representing several Aptian ammonite zones, with fossils derived from Oxford Clay, Ampthill Clay, Kimmeridge Clay, Portland Formation and Sandringham Sands (uppermost Jurassic). There is no mention of coprolites.

Gault and Upper Greensand Formation

The Gault Formation crops out below the Chalk escarpment from Wiltshire to Norfolk. It rests non-sequentially on the Lower Greensand and overlaps it to rest unconformably on Jurassic strata and the Palaeozoic rocks of the buried London Platform. It consists almost entirely of richly fossiliferous marine mudstones. The Lower Gault mudstones are dark grey, whereas those of the Upper Gault are paler grey, more calcareous and silty. Gallois and Morter (1982) divided the formation in East Anglia into nineteen beds on the basis of lithological and faunal characteristics. Thirteen of these have clearly defined erosional bases, and the sequence could be described in terms of a repeated ideal rhythm. The base of each unit was defined by a non-sequence: an extensively burrowed, phosphatised and possibly glauconitised erosion surface (Fig. 3). This is immediately overlain by siltstone or silty mudstone with abundant shell debris, fragmentary shells, abraded belemnites and black phosphatic pebbles including reworked phosphatised ammonites. The overlying mudstone becomes slightly paler and less silty upward. Shells are commonly crushed and preserved as aragonite. There is no mention of nodules in the upper part of the rhythms.

At many levels in the Thame District, phosphatic nodules grew *in situ*, commonly around fossils or burrows (Horton *et al*., 1995). Additionally, erosive non-sequences are generally marked by bands of bluish-black phosphatic pebbles. Most of these are nodules eroded from underlying beds, which have undergone further phosphatisation during reworking. These beds were worked at three localities between Thame and Aylesbury, probably from near the base of the Upper Gault. At Ford (SU790694) there were two seams, possibly within 1 metre, the main seam being 10 cm thick (Jukes-Browne and Hill, 1900). Pebbles collected from the restored soil surface during the resurvey were irregularly shaped; many are internal moulds of ammonite segments or bivalves, most show evidence of abrasion, and many are bored or show signs of encrusting epifauna (Horton *et al*., 1995).

In the Leighton Buzzard district phosphate was dug from high levels in the Upper Gault and Upper Greensand (Shephard-Thorn *et al*., 1994; Jukes-Browne and Hill, 1900). In the Sundon borehole, phosphate nodules occur in both the Upper Gault and the overlying Upper Greensand. In the former, some of the more phosphate-rich beds rest on an erosion surface and at one level contain oyster-encrusted nodules. At Buckland and Chaddington, near Tring, Jukes-Browne (1875) described excavations that yielded beds with numerous black phosphate nodules. The phosphatic material at both these sites may actually be pebbles.

Despite the large number of cored boreholes drilled through the Gault and examined by the British Geological Survey, not one coprolite has been recorded. Curated specimens from the boreholes of Arlesey (TL189346) and the Ely-Ouse No.14(TL696812) have phosphatic trace fossils within bed 16 of the standard Upper Gault sequence. These are crushed trace fossils that were originally cylindrical burrows 15 mm in diameter and lined with undigested organic remains (Fig. 11). These have a clear amber-like preservation and include fish spines and scales with growth rings. A similar fossil was found in a borehole at Duxford (TL481454) near Cambridge. Phosphatic nodules and pebbles occur throughout the formation.

Cambridge Greensand Formation

This formation was the major source of commercial phosphate. In the Chilterns a thin bed, the Glauconitic Marl, occurs at the base of the Chalk and locally contains small brown phosphatic pebbles (Horton *et al*., 1995). Traced northeastward in the Leighton

***Figure 11**. Trace of a burrow lined with fish and crustacean debris, in the Upper Gault at a depth of 132 m in the Duxford Borehole, in core that is 76 mm in diameter.*

Buzzard district it proved difficult to map the boundary where silty textured Glauconitic Marl overlies silty glauconitic mudstones of the Upper Greensand. The lateral transition from Glauconitic Marl to Cambridge Greensand is near Shillington, Bedfordshire, where pale phosphate pebbles characteristic of the Glauconitic Marl are replaced by dark phosphate pebbles.

For many years, the age of the Cambridge Greensand was controversial. The published evidence shows that the Cambridge Greensand is a basal conglomerate of the Chalk Group. It is a condensed deposit and the basal bed contains moulds and casts of fossils including ammonites (Fig. 12). Casey (in Edmonds and Dinham, 1965) concluded 'it is clear that the phosphatised faunas for which the Cambridge Greensand is famed contain no closely datable elements that are not Upper Albian. Though it may well be true that the deposit was finally laid down in Cenomanian times'. Hart (1973) concluded on the basis of foraminiferal assemblage zones, that some parts of the Cenomanian stages were absent. Cambridge Greensand contains a remanent fauna of phosphatized fossils characteristic of the higher Gault and Upper Greensand and an indigenous Cenomanian calcareous fauna (Hopson *et al*., 1996).

The importance of this non-sequence was noted by Seeley (1866) who described the overlying lithology as dark nodules in a soft matrix of marl and glauconite 15-30 cm thick resting on an irregular surface. It contains a few large stones up to 30 cm in size, including granite, hornstones, quartzites and sheared rocks, some of which are overgrown with oysters. He noted that many concretions are rolled and recorded bones of birds, ichthyosaurs, crocodiles and lizards. He states 'the dark phosphatic nodules usually named coprolites'. No name could be more unfortunate, for there is no evidence of their coprolitic origin; the only coprolites found, those of small fishes, are among the rarest fossils of the bed.

Chalk Rock Member, Upper Chalk Group

Phosphate occurs as hardgrounds in the Chalk Rock Member, which occurs at the base of the Upper Chalk in eastern and southern England. In the Hitchin area the main phosphatic horizon is at the top of the Chalk Rock (Hopson *et al*., 1996). The hardground was described as a highly convolute surface mineralised by both calcium phosphate and glauconite, and both the surface and the underlying bed of chalk stone are penetrated by thalassinoid burrows. The surface is overlain by a bed of indurated chalk containing glauconitised and phosphatic pebbles, which also yields superbly preserved mineralised internal moulds of original aragonite shelled molluscs (notably ammonites), an association previously noted from older strata. They concluded (on p. 54) that mineralised hardgrounds developed on the contemporary sea floor during breaks in sedimentation.

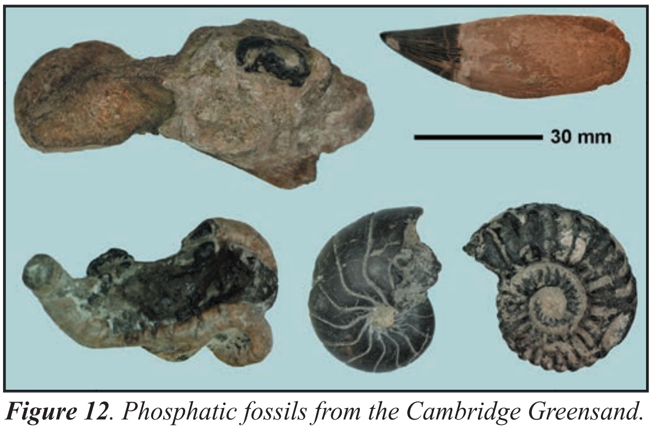

Figure 12. *Phosphatic fossils from the Cambridge Greensand.*

Neogene

Coralline Crag

The Coralline Crag comprises shallow-marine, shell-detrital sediments that are thought to be of late Pliocene age (Sumbler, 1996). The formation has a small outcrop near Aldeburgh, Suffolk, and contains three phosphate pebble beds. The basal bed was first excavated for fertilizer in 1820, but the phosphate industry developed from 1846 with the discovery of superphosphate (Ford and O'Connor, 2009), and peaked locally in 1857. It has been described as a 'remanié bed' (Boswell, 1927) and as a 'basal conglomerate lag deposit' (Balson, 1999). Its phosphate and calcareous mudstone pebbles were derived from the London Clay, whereas large flint pebbles, quartz, igneous rocks, bones and teeth came from older rocks. Rare in the Crag gravel are cobbles of Suffolk Boxstone, a muddy and slightly glauconitic sandstone with phosphatic cement, commonly enclosing casts of fossils. These are thought to have been derived from Neogene strata that are no longer preserved.

Red Crag

This formation rests unconformably on the Coralline Crag and comprises high-energy, shallow-marine shelly sands. A discontinuous conglomerate, widely exploited for phosphate, occurs at or near the base. Phosphate pebbles also occur in discontinuous layers and are scattered at higher levels. The basal bed, the Suffolk Bone Bed contains phosphatic mudstone pebbles derived from the London Clay, some of which contain crab and lobster remains. Shark and ray teeth are associated with rolled bones of walrus, cetaceans

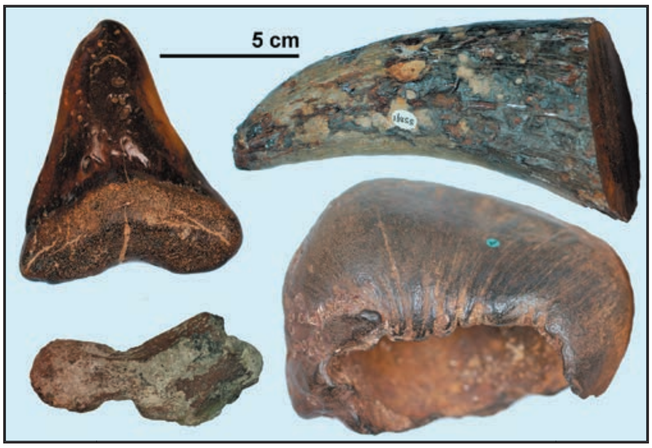

Figure 13. *Phosphatic fossils from the Pleistocene Red Crag.*

and the terrestrial mammal Mastodon (Fig. 13). Other pebbles include Suffolk Boxstone, Coralline Crag, flints, Jurassic limestone, quartz and quartzite with Mesozoic fossils including belemnites (Balson, 1999).

Conclusion

The phosphate in these Mesozoic and Cainozoic deposits generally occurs as either authigenic (*in situ*) nodules or as allogenic (derived) pebbles. Many of the latter comprise reworked nodules and phosphatised animal remains, particularly ammonites. Small amounts of derived phosphatic bones, fish teeth and scales may occur at the base of major discontinuities. A unique feature is provided by the phosphatic pisoliths in the Whitby Formation. The rarity of coprolites is notable, and it is recommended that future use of this term is restricted to confirmed fossil faeces.

An equally valid view is expressed by Ford and O'Connor (2002) in their description of coprolite mining that was a major industry in the latter half of the 19th century. The term coprolite was then applied to all phosphatic material whatever its origin. Having quoted the Oxford English Dictionary definition of coprolite (a stony roundish fossil consisting of, or supposed to consist of, the petrified excrement of an animal), they extend the usage to include phosphatic nodules. Purists might wish to refer to the latter by terms such as pseudo-coprolites, or false coprolites for those that cannot be shown to be excretions. The debate continues.

Acknowledgments

This review is based on the detailed description of sedimentary rock sequences by members of the British Geological Survey and the published accounts of many former colleagues, particularly B.M. Cox, R.W. Gallois, M.G. Sumbler, A.W. Morter and P.S. Balson. Drs E.R. Shephard-Thorn, A. Whittaker and T.D. Ford kindly read the text. The typescript was prepared by P.A. Horton, the figures were drawn by J. Smalley, and some photographs were from C.W. Wheatley, L. Neep and J. Harrald.

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An early-19th century geological map of the Peak District by John Farey

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Abstract: The incomplete geological map of the Peak District, compiled in 1808, is recorded and reproduced in part for the first time, together with a discussion of the background to its production and re-discovery.

John Farey senior was a pioneer of geology, and especially in Derbyshire, as shown by his massive three-volume *General View of the Agriculture and Minerals of Derbyshire* (1811-1817). This survey of Derbyshire, which uniquely included minerals, had been instituted by Sir John Sinclair, President of the Board of Agriculture, on the recommendation of Sir Joseph Banks, President of the Royal Society. Sinclair had commissioned Farey by a letter dated 14 August 1807 (copy in Sutro Library, California, Ag. 3:43), in which Sinclair had already agreed to Farey's wish, to give

> *in addition to the usual particulars discussed in the Agricultural Reports hitherto published, to enter more fully into all questions connected with the surface and soil of the District, than has hitherto been attempted.... [Sinclair having previously received a letter from Banks] who seems much impressed with the idea that a corrected Report of Derbyshire, drawn up by you, will be a valuable addition to the surveys now going forward.*

Sinclair then agreed to initially pay Farey £300, and to allow the period for its delivery to be extended to May [1808]. On the copy of this letter which Sinclair had sent to Banks, that same day, Banks noted "not a syllable in my letter has a Reference to the increased price offered to Mr. Farey. I think he will deserve it if he is able to give a distinct account of the Stratification of Derbyshire, but whether he is or not remains to be known" (Sutro Lib. Ag. 3:44). How well Farey succeeded in assuaging Banks' doubts, at least in this Derbyshire *Agricultural Report*, is now a matter of record, but sadly Farey was to fail with his other geological projects in Derbyshire.

His project for the Board of Agriculture

Farey was able to commence his Derbyshire field work for the Board in September 1807, which continued until December 1809 (*Derbyshire*, 2, p. viii). But, because of delays at the Board of Agriculture and its then publisher Sir Richard Phillips (1767-1840) who had been declared bankrupt in October 1810 (*Morning Chronicle*, 29 October 1810), volume one (which contained most of the geology and mineralogy) could not be issued until June 1811 (*English Chronicle,* 23 June 1811). A biography of John Farey, and a list of some 250 of his publications was published in the 1989 reprint edition of this volume 1 (Ford & Torrens, 1989) and which was also included in the compendium volume on the *Practice of British Geology* (Torrens, 2004, 1-44).

Farey's *General View of 1811* includes only a single carefully coloured outline sketch map (*Derbyshire,* 1, opp. p. 97) to illustrate the county's geology, using nine different colours. But Farey is known to have planned from the very beginning a detailed "Mineral History and large Map", at a scale of 1 inch to 1 mile, to which he often refers. This was to have comprised his major work on the "Mineral History of Derbyshire, and its Environs, with a map of it, 1 inch to 1 mile". But, of this project, Farey had later to write, in 1817, how "the probable period of publishing my intended large Map and Mineral History... was now more distant" (*Derbyshire,* 3, p. 207).

Any modern equivalent project would certainly contain a large scale geological map in explanation, but with his Derbyshire project, Farey was very much acting as a "guinea pig", since his *Agricultural Report* for Derbyshire was the only one to contain full details of any county's geology (unlike all the other such *Reports*). The first author was first helped, from 1981, with locating Farey holdings at the Sutro Library in San Francisco, by a great great grandson of John Farey, Art Farey (1905-1992) then of nearby Oakland. But it only became possible to study the extraordinary detail, and colouring, of Farey's Derbyshire maps when the same author could explore the Sutro Library in person, in 1992 and again in 1996.

Adolph Sutro and his library

The Sutro Library, in San Francisco (in the J. Paul Leonard Library, on the State University campus) has long held a major collection of the papers of Joseph Banks, one of Farey's most significant patrons. Adolph Sutro (1830-1898) had made his fortune from gold, and other Californian mining, and soon became a major book, and manuscripts collector (Davidson 2003). He had been able to buy much of the Sir Joseph Banks archive when it was stupidly "scattered to the winds", at a series of London auction sales between 1880 and 1886, by later members of the Banks family (Carter, 1987). But soon, much of Sutro's wonderful collection of books, held in a warehouse on Battery Street, San Francisco, was destroyed in the fires, which followed the San Francisco earthquake in 1906. But Sutro's manuscript collections, in the separate Montgomery Block, including these Banks papers, in which were a number of Farey manuscripts, miraculously survived.

Figure 1. Part of Farey's map; the insets of the key and title block are not in their original positions, on a sheet that extended far beyond the area with the geology.

These Banks papers include an incomplete geological map of Derbyshire (Sutro M. 2:24) dated September 1808 by Farey, which is here reproduced in part for the first time. This geological map had been hand coloured onto the printed topographical map, published by C. Smith, 172 Strand, London, in 1804, on a scale of 3 miles to the inch. This 1804 map was confusingly listed, as by Farey, by Carter (1987) who failed to realise, never having seen it, that Farey's were only these geological additions. The map is clearly also the same "mineralogical map of Derbyshire by Mr. Farey laid before the Geological Society by the President, from Sir Joseph Banks, on 2 December 1808" (Geological Society, Council minute book).

The geology shown is understandably incomplete, since it was produced only one year after Farey had started his Survey. Farey's explanation of it reads

The STRATA, distinguished by Colours, as in the Explanation below, by John Farey, Mineralogical Surveyor, Sept. 1808, [which hand-drawn Explanation occurs in the southeast margin, which shows the sequence from] Second Coal Shale, down to the Fourth Limestone, below this the Strata are unknown, but are supposed to be Limestones and Toadstones alternating. N.B. The red dotted Lines show the Faults or perpendicular disarrangement of the Strata; the green dots the Shale Limestone, the red dots the Quartz Gravel.

Such colouring is only shown on the northwest quadrant of the map, from Ashbourne to the Edale valley. The map thus covers much of the limestone outcrop of the White Peak, but only a little of the Millstone Grit country north of Buxton and along the Derwent Valley. The limestone country south of a line approximating to the Bonsall Fault is coloured as though it was all the Fourth Limestone, and the dolomitized area now known around Brassington had not yet been distinguished. No detail understandably was given of any outcrops in Staffordshire. Stratigraphic subdivisions of the limestone country are coloured separately. Together, these show that Farey had already recognized the sequence of alternating limestones and toadstones, as he named later in his *General Survey* and then numbered downwards; “First Mineral Limestone”, “First Toadstone”, “Second Limestone”, “Second Toadstone”, “Third Limestone”, “Third Toadstone”, to “Fourth Limestone”. The stratigraphic column above these limestones is also recorded, upwards, starting with “Limestone Shale and Shale Freestone”, then “First, or Millstone, Grit”, “First Coal Shale”, “Second Grit Rock” to “Second Coal Shale”. Only the lowest two divisions of the Millstone Grit Series are shown on the map, but none too clearly.

Another hand-written note adds that “faults are indicated by red dotted lines”, but the only major example Farey shows is that all around the limestone-shale boundary, all the way between Wirksworth, Buxton, Hartington, Waterhouses, Ilam to Cromford.. Farey was evidently puzzled by the proximity of the Fourth Limestone to the shales, a contact now known to be due to an unconformity, with Edale shales banked up against Bee Low Limestones. A separate drawing entitled “for explaining th[is] fault, as shown in J. Farey’s small Map of the great Limestone District in Derbyshire, made for Sir Joseph Banks, 9 September 1808” survives elsewhere in the Sutro Library collection (Geol. 1:2a). Again Farey, as a pioneer, had faced problems in explaining such an abnormal contact. It could be due either to faulting, as Farey assumed, or to unconformity (as we know today). But the concept of unconformity was then hidden to English geologists, however well it was understood by Scottish ones as a result of James Hutton’s explanations. Tomkeieff (1962) has explained this problem well, and Challinor has discussed the particular problems which Farey faced with this supposed Great Derbyshire Fault (1976).

Few of the many other types of fault later illustrated in Farey’s fold-out diagram in the *General Survey* are shown. No mineral veins are indicated. The outcrops of the First, Second and Third Limestones are reasonably close to the presently known distribution of the Eyam, Monsal Dale and Bee Low Limestones respectively, with the Fourth Limestone being anything below these.

Farey had also finished, in February 1808, a long section between Lincolnshire, passing through Revesby, Banks’ Lincolnshire seat, to his Derbyshire seat at Overton, started in the autumn of 1807, and some 3 metres long (Sherborn, 1929). Although several hand-drawn copies were circulated, this section, like Farey’s others across the Peak District (1808) and Sussex (1807), was not published until reproduced by Ford (1967). Farey’s 1812 Hampshire section was only first published by Ford and Torrens (2001). But the Sutro collection additionally includes “A [coloured] Section of Strata of the great Mineral Limestone District and its bordering Strata in Derbyshire, passing thro’ Buxton and Bakewell; shewing the great Faults and Denudation of the Strata between Goyte Moss and Baslow Collieries, as represented in the Sketch from Mr. John Farey’s Mineralogical Map, September 1808” (Sutro, M 2:22). This shows the same western part of Farey’s Peak District section as in that reproduced by Ford (1967).

Farey’s Ashover project

Farey had also been separately commissioned by Banks to prepare a private, “mineralogical survey” of Banks’ large Ashover estate, centered on his Overton Hall, on which Farey first worked from Autumn 1807 to 1809 (Torrens, 1994). This included a very detailed geological map of the area around Ashover, for which Farey had first - in such pre Ordnance Survey days - to construct the base map himself. This included Banks’ estate and mines there, which Farey drew up and finally completed late in 1812. Dated December 1812, this too survives, but now only as a “reduction of the Large Survey of Ashover Parish and its Environs”, in the Sutro collection (M 2:25; Torrens, 1994).

William Milnes junior (1785-1866) of Ashover, who was elected an Honorary Member of the Geological Society in 1810 (Woodward, 1907) had written to Banks’ friend John Lloyd (1749-1815) of Wygfair, in North Wales of this Ashover project, on 17 September 1811

Farey is now here busily employed along with Mr Nuttall [George, Banks’ Ashover estate agent] in making a mineral map shewing the range of all the Veins of Lead ore with the bassets [outcrops] of the different strata correctly laid down, and he is also to write a history of this very curious valley. When completed it will, I think, be a very entertaining as well as useful compilation. Sir Joseph has entered into it with great spirit and seems disposed to spare no expense in having it finished in the most accurate manner (National Library of Wales, 12420D, no. 35).

Milnes’ next letter, dated 1 December 1812 (no. 36) continues

Mr Farey, and his son William [1795-1836], came here about a fortnight after you left us, and they continued with us till the 9th of November. He worked very hard and finished the first and second circle of the Grit Stone round this parish and next year, I hope, he will be able to complete his mineral map which I think will be one of the most interesting things ever published in this *county. He desired me to say that he was much obliged to you for thinking of him and if you could prevail upon the gentlemen in your neigbourhood to employ him, he is so fond of the pursuit [mineral surveying] that if they thought 2 guineas a day for him and his son too much he would come for less.*

This, clearly still incomplete, map of December 1812, also remained unpublished, until it was reproduced by Torrens (1994) and then used as a cover of *Geology Today* (Ford & Torrens, 2001 - where Farey's unit three was more correctly interpreted as Edale Shales [not Head and Boulder Clay]).

This truly remarkable map has since been discussed by David Oldroyd, who claims, that "if one did not know the date, one might easily suppose by its appearance that the map was a late nineteenth-century production" (Oldroyd, 1996, 114). More recently he has discussed the significance of this forgotten map in a much wider context. Now he calls Farey "a genius", and his map "astonishing (which by its appearance might have been made at the end of the 19th C)". The Ashover area later became a major training ground for geological mapping to generations of British undergraduates, including the first author in 1960, when we used the maps produced by Sweeting (1946) and then by Himus and Sweeting (1955). If only we had then known how far we had then failed to reach the high standard set by Farey nearly 150 years before!

His Derbyshire project abandoned

Farey's long Memoir on the Ashover Denudation, to accompany this Map, was duly read for him to the Geological Society of London on 2 and 23 April 1813. The Geological Society's Council Minutes of 2 April 1813 already ominously record how this first part already "consists of minute local observations incapable of abridgement". This Memoir was to comprise much of his planned "Derbyshire Mineral Map and Section". But none of these were ever published; "being rejected, through the intrigues of a few individuals, by the Geological Society" (see Farey to James Sowerby, 7 July 1813, Eyles Collection, University of Bristol library). Farey soon gave full details of his treatment at the hands of the Society in his published letter, dated 16 July 1813 (Farey, 1813). This related how his Memoir, of 120 folio pages, was first presented on 4 February 1813, with a mineral map covering the strata of more than 30 square miles on a scale of 1 and a half inches to a mile, along with, by President Greenough's desire, a large cross section across more than seven miles with another map half a mile wide on a scale of 10 inches to a mile, which section had been "conditionally left with the Society in March 1812 by Banks formerly a member (until February-March 1809)".

Farey relates how about a month after his Memoir was read, Greenough had introduced to him "the gentleman who was to edit the forthcoming volume of the Society's *Transactions"*, This was the politician Henry Warburton (1784-1858) who was elected a Member in 1808. Farey records how Warburton told him the Council were averse to the publication of Farey's paper and who "believed he could say so of every individual thereof, but of this fact he produced no proof, nor have I the opportunity to the present of learning in a regular way any opinion or decision whatever of the Council, or the nature of the objections that have been privately raised". Instead Warburton had produced a new, much abridged, version for Farey, who understandably objected, because of "the inordinate compression it had suffered". Farey was also baffled at the way "loose and inapplicable Anglo-Wernerian terms" had now been added; "having been told by a member of Council that if I did not use Wernerian Terms nobody would read my paper". Later, Farey regretted he had not taken more note of this hint and thus "avoided the loss of many weeks of my time this spring and subsequent vexation".

That Warburton was responsible becomes clear from two undated letters to Greenough, probably from June 1813

I send you the paper in a state, as I conceive, [now] fit for publication. but unless the Gentleman [Farey] engages to return this Abridgement, I do not wish to part with it without first having taken a Copy. He seems to be angry beyond measure. Perhaps if I were to meet him at your house to breakfast on Thursday morning something might be done? I do not wish to bring him, as he lives on the fruits of his labour, out of the way to my part of the town, as this may form a new subject of accusation, Surely 70 pages of quarto letter press are enough for him? (Greenough MSS, University College, London, Add. Mss. 7918, no. 1684).

From this one has confirmation of the extent of the planned abridgement. 120 folio pages had become 70 on quarto, a reduction of about half. Clearly another 'bone of contention' lay in the gulf between the different worlds of the 'gentlemen geologists' of the Geological Society (with Greenough, editor Warburton and secretary Henry Grey Bennet (1777-1836) all rich Old Etonians, active in politics, supported by private incomes, against the 'mineral surveyors', who had to earn precarious livings, using their new, and still unaccepted, knowledge.

Farey's 1819 attempt to publish his map

Much later, a notice in the *Derby Mercury* (28 October 1819) headed "Farey's Large Map of Derbyshire" recorded that Farey had completed his map, in two states, one mineralogical and geological, the other topographical, and that it would now "be prepared for sale", together with "an explanatory memoir, and that they were to be sold by John Cary, the publisher of Mr. Smith's and other Geological Maps, Sections at No. 181 Strand, London".

"Mr. Smith" was William Smith (1769-1839) who had introduced Farey to the science of geology and its stratigraphic column, for use in mineral surveying, whilst they had both been employed by the Duke of Bedford at Woburn, Bedfordshire over 1800-1802. Cary had commenced the publication of William Smith's planned series of *County Geological Maps* early in 1819, but which had only managed to cover 21 counties, before the project was abandoned in 1824 (Eyles, 1969). Derbyshire was not among them, so Farey's map must have been intended to fill this gap. Sadly Smith's County Maps are excessively rare today, so had clearly not proved a commercial proposition in an England slowly emerging from recession, after years of war with the French (against which Farey also fought equally tenaciously as a pacifist). Farey and Smith both suffered from the still current lack of awareness of the value of geological knowledge. When his *Derbyshire Survey* was finally finished, with the publication of its third volume in October 1817 (despite the first volume having been re-printed in 1815) sales of the three had proved very low. As a result the complete set is today an exceedingly rare item. Stuart Baldwin's catalogue of December 2000, which offered a complete set, noted "it was the first he had seen in 30 years". One of Wheldon and Wesley's last catalogues, of February 2001, offering another, confirmed this, stating "we have not had this work since 1957", i,e for a period of 44 years!

So it was against these financial, and cultural, backgrounds that Farey's Derbyshire map was advertised, but then never appeared. Farey had been paid a total of £450 for his work on the *Derbyshire Report*. But it was not just sales of his books, and maps which had suffered, but Farey himself. In February 1819 Farey had had a printed appeal for work, from "The Owners and Lessees of Coal and other Valuable Minerals", published, on the cover of the *Philosophical Magazine* for February 1819, (volume 53, no. 250). Then, on a 14 March 1819 letter to Jonathan Otley, he used a similar appeal as his own printed letter-head (in Jonathan Otley papers, courtesy of David Oldroyd). Though advertised in this newspaper notice, neither the completed map, nor any memoir ever appeared. Clearly Cary (or Farey) had decided against publication, simply on commercial grounds. Cary had long experience of the problems of publishing such items in an ignorant Britain. In addition he had recently moved his workshop from the Strand between July 1819 and March 1820 (Fordham, 1925). If only Farey's complete Derbyshire map could have been published, it would have been a great advance on any previous area map. Farey's work here was a remarkable achievement here when one realises he had had to start completely from scratch. His tragic final years and the loss of his manuscripts have further been discussed by Ford & Torrens (1989).

Acknowledgments

The late Art Farey, Roger Flindall (Long Eaton), who first led us to the 1819 advert, Frank Glover (at the Sutro Library, San Francisco), Leo Laporte (Redwood City) and David Oldroyd (Sydney) gave us all the help we needed to complete this work.

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MEMBERS' EVENING

The sixth Members' Evening was held on 21st April 2012. Once again, the instructions to the presenters were simple: *show us your interests and infect us with your enthusiasm*. It is hoped that other members, especially those who are amateur, will offer short presentations to continue the success of the Members' Evenings into future years. This year, Richard Hamblin also presented a talk on the Cretaceous Greensand, which will form a short paper in next year's *Mercian Geologist*.

BRITPITS Mines and Quarries Database

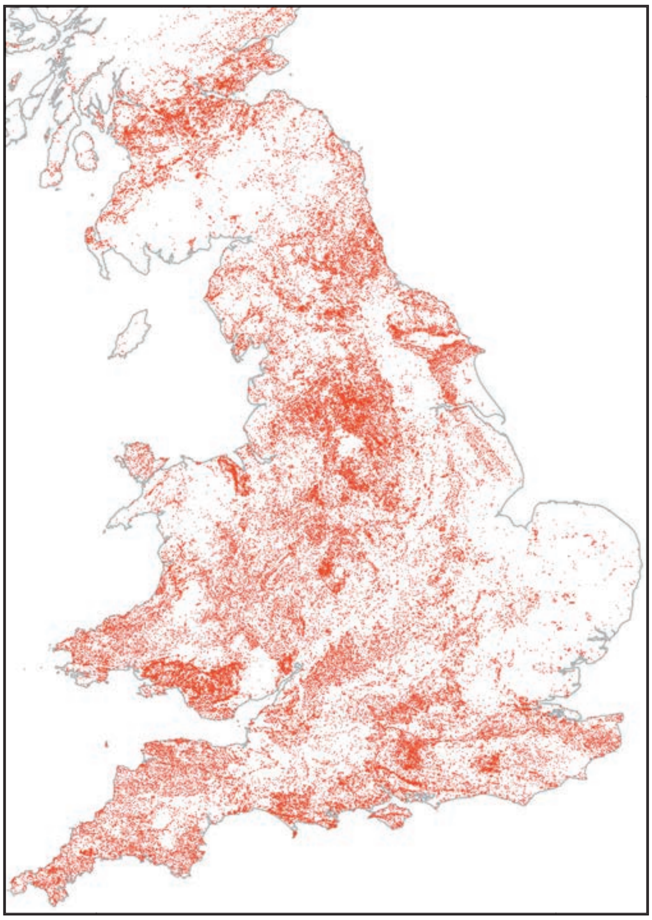
Don Cameron

A national database of mine and quarry information has been part of the Geological Survey since its earliest days. In 1845 at the invitation of Sir Henry De la Beche, Director of the Geological Survey of Great Britain, Robert Hunt went to London and took up the post of Keeper of the Mining Records of the Survey. When the Government School of Mines was established in 1851 he was made a Lecturer in Mechanical Science and then in Physics. Part II of the *Mineral Statistics of the United Kingdom of Great Britain and Ireland for the Year 1858,* 'Hunt's Statistics', was produced in 1860. This attempted to be 'Embracing Clays, Bricks &c., Building and Other Stones with Sundry Earthy Minerals'. In a notice at the beginning, the then Director, Roderick Impey Murchison wrote *'The present publication is the result of a first attempt on the part of Mr. Robert Hunt to collect returns of the produce of the Clay Works and Quarries of the United Kingdom. Though a large amount of useful information has been obtained, it must be admitted that this branch of our Mineral Statistics is, as yet, far from complete. Let us hope, however, that the work now issued may lead many persons who have withheld information, to render the next edition more worthy of public attention.'* This was based on figures gathered in 1858 for production by each commodity, and the complaint of the Director has been echoed by compilers down the years.

As was normal in those days, the database resided in a series of books, listing active workings, published yearly, firstly by the Geological Survey and later by the Inspectors of Mines, as a List of Mines and a List of Quarries. The List of Quarries continued until 1948, although lists were produced by HSE and other bodies. The List of Mines was taken over by the Colliery Managers Journal and published as the Guide to the Coalfields, which lasted until the 1990s. In 1984, BGS decided to publish a Directory of Mines and Quarries, listing some 2500 active mineral workings and their operators, together with, for the first time, the body of rock worked at the site.

The Directory has subsequently been produced, initially bi-annually and latterly tri-annually, up until the latest edition covering 2010. At the same time steps were taken to design a digital database (BRITPITS) to store the data. At first this was resticted to the active sites, however it was seen that holding records of ceased operations would assist the minerals planning process, especially when the database could be incorporated in a Geographic Information System. Currently, the BGS BRITPITS database holds around 152,000 records of mineral workings in the UK. The database has been used to provide baseline information for mineral resource maps for planners, and is currently used by the English Heritage Strategic Stone Study project to locate quarry sources of building stones. BGS makes some of this data available through its website, and in the future, all of these records will be visible on the web. Data collection is still continuing, and once there is baseline coverage of the country, it is hoped that revision of the data will allow early records to be brought up to the standard of those collected more recently.

The quarry data may be viewed on the BGS website as part of the GeolIndex layers at mapapps2.bgs.ac.uk/geoindex/home and at MineralsUk.com. The latest edition of the Directory may be downloaded from www.bgs.ac.uk/mineralsuk/mines/dmq. The building stones study and database is at www.bgs.ac.uk/mineralsuk/mines/stones/EH_project.



Mineral workings in England, Wales and southern Scotland, from the BRITPITS database in July 2012. Baseline coverage is currently incomplete for parts of East Anglia, Wales and Scotland (courtesy of BGS).

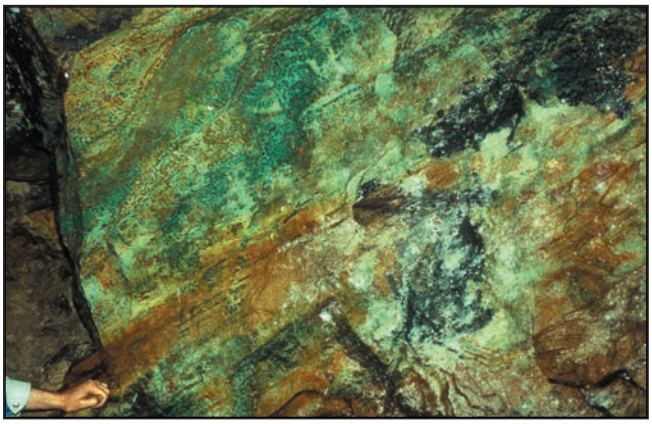
The Legacy of Mining at Alderley Edge

Geoff Warrington

The Cheshire Basin is an asymmetric, north-south-trending, post-Variscan graben structure that accommodates a thick succession of Permian, Triassic and lower Jurassic sediments. The Triassic sequence includes arenaceous formations of the Sherwood Sandstone Group, overlain by argillaceous and evaporitic units of the Mercia Mudstone Group. Barite mineralization and, at scattered localities, small metallic ore deposits, principally of copper, but including lead and smaller amounts of cobalt, manganese, nickel, vanadium, zinc and other elements, occur in the sandstone. The main site where these ores were mined is Alderley Edge, in the northeast of the basin, 15 km south of Manchester (Warrington, 1965, 2010).

The Alderley ore deposits were originally considered to be syngenetic but have, for the last 50 years, been regarded as epigenetic. Alderley Edge is a 3km-wide horst that lies between major N-S-trending faults. Formations of the Sherwood Sandstone are now exposed in the horst but were formerly covered by a seal of Mercia Mudstone and the structure was, therefore, a potential trap for migrating fluids. In lectures in Manchester in 1977 the writer proposed that the mineralizing fluids were low-temperature, intrastratal basinal brines that migrated into this trap where the ores were deposited under reducing conditions, possibly created by hydrocarbons that accumulated in the same structure (Warrington, 1980). This basic model has since been substantiated and refined by others. The primary mineralization is now considered to have occurred in late Triassic to early Jurassic times, as part of the diagenesis of the host-rocks (Plant *et al.*, 1999). Extensive alteration occurred in the Cenozoic, and over sixty mineral species, mostly secondary, have been recorded from the locality (Braithwaite, 1994; Warrington, 2010).

The sandstone sequence exposed at Alderley Edge comprises the Wilmslow Sandstone and overlying Helsby Sandstone formations. These dip SW at 10-15º and successively higher units in the Helsby Sandstone crop out across the horst. Metallic ores occur almost exclusively in the c.100m-thick Helsby Sandstone that includes members of both fluvial and aeolian origin and is succeeded by the lowest (Tarporley Siltstone) formation of the Mercia Mudstone.



Disseminated copper ore (malachite and other secondary minerals) in aeolian sandstone in West Mine.

Fault zone with associated barite (pink) and massive galena (grey) in the Engine Vein mine; a stoped-out area extends into sandstones in the footwall to the right.

Over 15 km of disused mine workings at this site afford a unique opportunity for the study of the mineralization and sedimentary features in the red-bed host rocks in an unweathered state and in 3D. The mine workings comprise three units that, from east to west, give access to three successively higher ore-bearing levels in the succession, and to host rocks and structural situations of different character at each level. In the east, in the Stormy Point and Engine Vein mines, mineralization occurs in the topmost Wilmslow Sandstone and the basal Helsby Sandstone; fluids were trapped in footwall sandstones adjacent to faults, and below mudstone beds that form aquicludes in the Helsby Sandstone. The ore bodies here were narrow, linear, and strongly fault-controlled. In the central area, in a member higher in the Helsby Sandstone and seen in Wood Mine, mineralization occurs in a succession of eight or nine fining-upward, fluvial sedimentary cycles. Mudstone beds in these cycles, and others containing debris from the erosion of such beds, formed complete and partial aquicludes respectively, and resulted in irregular and discontinuous, but more extensive, ore bodies. Farther west, in West Mine, an aeolian sandstone higher in the Helsby Sandstone contained very large,

Part of a stope in West Mine left after the extraction of a large body of copper ore hosted by aeolian sandstone.

more continuous, ore bodies, reflecting the relatively homogeneous nature of the host rock at that level.

The open stopes left by mining reflect the size, form and disposition of the ore bodies and offer a unique opportunity to observe the influence of structure and host-rock facies on the migration of the mineralizing fluids. They can, by analogy, aid visualization of the influence of those factors on the migration of other fluids, such as hydrocarbons, and afford the opportunity to 'step inside a reservoir'.

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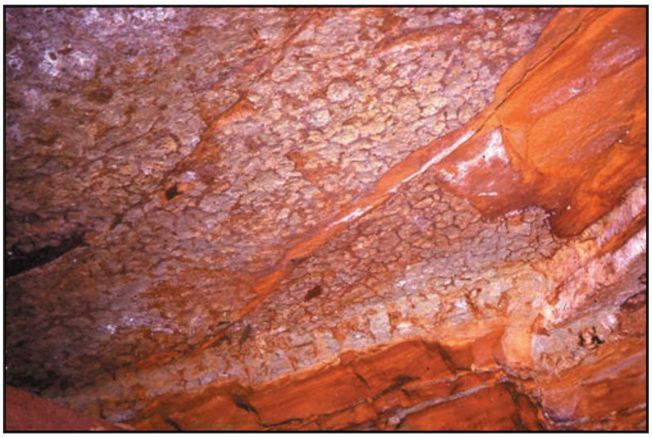

Mudstone bed with mudcracks seen in section and from the underside, in the roof of a stope in the Engine Vein mine.

REVIEW

Scottish Agates by Nick Crawford and David Anderson, 2010. Lapidary Stone Publications, 978-0-9558106-1-9, 208 pages, 800 colour illustrations, £14.99.

This splendid book is accurately summarised by the back cover description: 'Scottish Agates provides a comprehensive account of the agates of Scotland including more than 800 full colour images, an in-depth exploration of where these beautiful stones can be found, a description of techniques for their preparation with information on their history and use in jewellery'

Scottish agates are generally restricted to areas underlain by basaltic lava flows, especially in the Midland Valley. The book is written by two enthusiastic collectors and is illustrated by the hundreds of excellent colour images of sawn and polished specimens, together with numerous locality photographs and small-scale colour maps of the six main areas where they may be found. The first 7 pages describe the geology of Scotland followed by a somewhat unnecessary (though interesting) 16-page summary of Earth's history, with world maps of continental reconstructions, followed by 12 pages of how Scottish agates are formed. The bulk of the book contains details of the sources (quarries, streams and fields) of the agates found in each of the principal areas, illustrated with dozens of images of specimens and landscape photographs for each area.

The book is completed by brief descriptions of collecting, cutting, polishing and imaging techniques, Scottish agate jewellery and artefacts, collectors and their specimens and a comprehensive bibliography and useful index

If there is any criticism it would be that there are too many images of the agates: to cram them all in they are mainly necessarily small (5x4cm). A reduced number of larger images of the most important specimens would be an improvement; the larger half-page images scattered through the book attest to this. Excellent landscape photographs of agate-bearing areas are also too small and could usefully be enlarged. There are no Grid References to quarries or other localities. This may be deliberate, to discourage casual collection, and is difficult where areas or lengths of rivers are involved.

This book is certainly comprehensive in its coverage of the subject and is abundantly illustrated with high-quality photographs. The heavy-weight paper feels good and helps the quality of the photographs and illustrations. It can be recommended as an excellent technical and visual source of information on this somewhat esoteric subject.

Tim Colman

REPORT

British Triassic palaeontology: new literature supplement 34

A review of British Triassic palaeontology was published by the writer in 1976 (*Proc. Ussher Soc.*, **3**, 341-353). Supplements to the bibliography appeared annually in that journal until 1986, and from 1987 to 2009 in *Albertiana*, the newsletter of the Sub-commission on Triassic Stratigraphy. To make information on new literature on this subject more accessible to British workers, the series continues in the *Mercian Geologist*, beginning with this supplement, number 34, compiled in the year to 29 February 2012.

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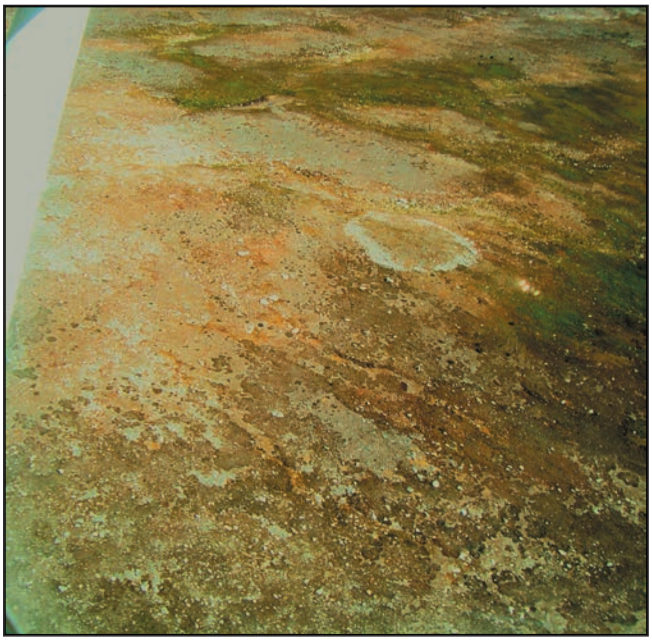
REPORT

Unusual stone circle in British Columbia

High above the Coast Range of British Columbia, Canada, a small float plane circles over a ring of stones before descending to the Nuk Tesli Alpine Experience, a group of log cabins situated by the side of Whitton Lake, some 500 m below. On board are two geologists, Michael Czajkowski, a lecturer with the Open University, and Andrew Okulitch of the Canadian Geological Survey.

They were there to investigate a circle of stones that is 50 m in diameter (it can be seen on Google Earth), situated above the tree line about 160 km in from the Pacific coast and 900 km north of Vancouver. Composed of pale felsite, the circle lies on a plateau veneered with glacial debris on top of darker, course-grained, sheared granite and granodiorite. The investigation suggested that a single large felsite block was transported by a glacier, possibly several kilometres. After most of the glacier had melted away, the isolated block protected a pedestal of ice that melted more slowly within the basal glacial debris. Freeze-thaw then caused break-up of the block, which was probably already fractured, and the fragments then slid off the sides of the ice mound to form the ring of stone debris.

Although solifluction has caused minor modification of the landscape, lobes and mounds inside the circle do suggest that an ice mound remained here for some time. Clasts that are larger and more numerous on the south side may reflect melting from that direction, creating a slope down which much of the rock fragments could slide. The circle's position on a gently inclined plateau ruled out an origin in circular patterned ground associated with pingo development. A literature search has found no report of any other structure of its type.



The stone circle seen from the air.

The terrain of the Coast Ranges; the stone circle is on top of the mountain to the right.

Local people had previously suggested causes for the circle that ranged from a meteorite crater to a man-made structure. Had the latter been proved, it would have had tremendous ramifications for ideas of migration of humans into North America. Man-made stone circles are rare in North America. A few known in the United States are smaller and contain spokes from a central hub. A few suspected man-made structures in British Columbia are much smaller, and all are found near known archaeological sites. This one is too high, even allowing for a warmer mid-Holocene environment, and no evidence of ancient man has ever been found in the area.

Even as a natural feature, the stone circle and its investigation were widely reported in the Canadian media. The full report, with more detailed discussion, was published in the Canadian Journal of Earth Science in 2011 (v48, pp1523-1529), and can be downloaded from www.nrcresearchpress.com .

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Andrew Okulitch and the author standing on the stone circle.

EXCURSION

Bradford Dale

Leader: Colin Bagshaw

This evening excursion consists of a walk of about 4 km return, mainly along part of the delightful valley of the River Bradford eroded mainly into limestones of Upper Visean (D_2 and P_2 Zone) age.

It begins in the village square of Middleton by Youlgreave (SK196632) where there is space for parking vehicles. Limestone buildings date back to the early 19th century when the village was rebuilt by the local lord of the manor, the archaeologist Thomas Bateman. It was then a centre of agriculture and lead mining. Of even older origin, at the northern edge of the village now occupied by Castle Farm, is the site of a 16th century castle that was a royalist stronghold during the Civil War. It was then occupied by the family of Sir Christopher Fulwood, who met an untimely end in the valley below after a skirmish with a troop of Roundheads led by Sir John Gell. By contrast, the village is now a haven of peace, and the well on the north side of the village square is dressed in the summer.

Bradford Dale is reached by the path to the east opposite the children's playground where there is also a memorial to the crew of a Wellington bomber that crashed nearby during World War II. Green Farm is to the right of the path, and nearby is Dale Cottage with a barn built of limestone, of which some blocks contain numerous fossils of brachiopods, corals and crinoids. Just beyond, take the left fork for the descent into the valley. Some 20m along the path, outcrops of the top part of the Monsall Dale (D_2) limestone contain shell debris. A further 50m down the path, more limestone outcrops contain bands of dark coloured chert beneath which are numerous colonies of compound corals (*Siphonodendron*, formerly known as *Lithostrotion*). Higher up, the outcrop contains the so-called Lathkill Shell Bed of bioclastic limestone with the brachiopod *Gigantoproductus*. The cliffs to the right of the path are topped by Eyam Limestone of P_2 age.

Further along the descent are scattered white "bricks" engraved with words making up various quotations created by the local community. This is one of the "Sites of Meaning" which make up a series of "Markerstones for the Millennium" in the area (see www.sitesofmeaning.org.uk).

The foot of the slope is at the River Bradford, where there are remains of a sheep dip, built with blocks of local gritstone. There are also indications of a former waterwheel pit that was used to raise a water supply up to Middleton village.

Continue along the path and where it swings round to the east a series of dammed ponds, each about 100m long, are interconnected by channels controlled by sluice gates. Constructed at the end of the 19th century, the ponds were initially designed to breed trout, which can still be seen in the clear water. The ponds are now the home to various water birds that build their nests in the more shallow water. A bridge over the river has its low wall inscribed with a quote from Wordsworth as a further "Site of Meaning".

The path then passes through a gate into the Haddon Estate and on the right is a steep scree slope that. The limestones dip gently to the east, so that the Eyam Limestone is gradually dipping down to river level. The screes, particularly alongside the fourth pond, are in part the waste from old lead mines, and careful examination reveals small specimens of calcite, barite and rare galena. Mineral occurrences increase towards the end of this pond where there is the ditch of a worked rake to the right, descending the valley side acutely. There are also blocks of basalt, commonly vesicular; this is the Lathkill Lodge Lava, with outcrops in the river bed that may be responsible for the river staying above the surface and not sinking underground.

One of the adit entrances to the Wenley Hill complex of old lead mines, lying to the south of Youlgreave, is just beyond the next pond. About 200m further on an old clapper bridge crosses the river to the left. To the right, a steep path up the valley side leads to another mine entrance at a fault in the thinly bedded, dark Eyam Limestone. This indication of the onset of more argillaceous sediments is confirmed a few metres further up the path where it reaches the top of the valley side and presents an open view to the south. The slope of the fields represents the dip to the southeast of the Namurian shale, leading down to the scarp of Ashover Grit that forms the skyline. To the left, the tips of the old Mawstone mine have been worked for fluorite in recent years.

Return to Middleton either by the footpath to the right across the fields, or back along the Dale, or cross the clapper bridge for the road into Youlgreave where an interesting church and several hostelries await.

The path along Bradford Dale.

EXCURSION

Upper Dove Valley

Leader: Neil Aitkenhead

Unlike Dove valley between Ilam and Alstonefield, with its limestone gorge scenery that is the best-known part of Dovedale, the upper Dove valley is largely floored by shaley mudstones of Namurian age. As a consequence, the valley is much more open, with gentle slopes flanking the river. However, the western margin of the Lower Carboniferous Derbyshire Carbonate Platform impinges on the northeast side of the valley, and is characterized by an apron reef limestone facies (Wolfenden, 1958). This comprises crudely-bedded, fossiliferous, micritic limestones generally dipping southwards at about 25-45°, the dip being largely depositional off the platform rather than tectonic.

The excursion's meeting place and first stop, on Sunday 4th September 2011, was a disused roadside quarry [SK089675], near Jericho Farm, just north of Earl Sterndale. The quarry exposes a weathered and etched face of finely crinoidal limestone with little evidence of current sorting; it exposes an overturned colony of the coral *Siphonodendron* (formerly *Lithostrotion*), indicating turbulent conditions in this platform edge location. The quarry also provides extensive parking, and offers an excellent view of the upper Dove valley with its remarkable apron reef limestone scenery including Parkhouse Hill, and Chrome Hill.

Next, cars were left in a substantial parking place [SK075675] at Dowall Hall. This lies at the southern end of Dowel Dale flanked by fore-reef limestones that have yielded the ammonoid *Goniatites moorei,* indicating an upper B_2 age (Aitkenhead *et al*., 1985). A mainly uphill walk of about a kilometre took us to the northwestern end of the Chrome Hill ridge. On the way we crossed hummocky ground that marked a substantial landslip in Namurian shales. We also examined a limestone slab covered in galena crystals on the fault plane of the Chrome Hill Fault that defines the northeast face of that hill. A few shallow overgrown pits indicate former workings for lead at this locality.

On the Chrome Hill ridge, looking towards Parkhouse Hill.

From the summit of Chrome Hill we enjoyed extensive views, particularly westward to Axe Edge and southwards to the hills around the Manifold and Dove valleys including Ecton Hill. We were able to see that the dip of the fore-reef limestones on the southwest slope of the hill is sub-parallel to this slope, indicating a dip-slope. The limestone dip has been shown to approximate to an original depositional dip.

As it was still only mid-afternoon, we then drove to Apes Tor in the Manifold Valley. Here, disused roadside quarries expose excellent sections in the intensely folded limestone turbidites that comprise the Ecton Limestones Formation. These beds are a remarkable contrast to the thickly-bedded, gently dipping limestones of about the same age seen earlier around Earl Sterndale and on our route down Long Dale into Hartington.

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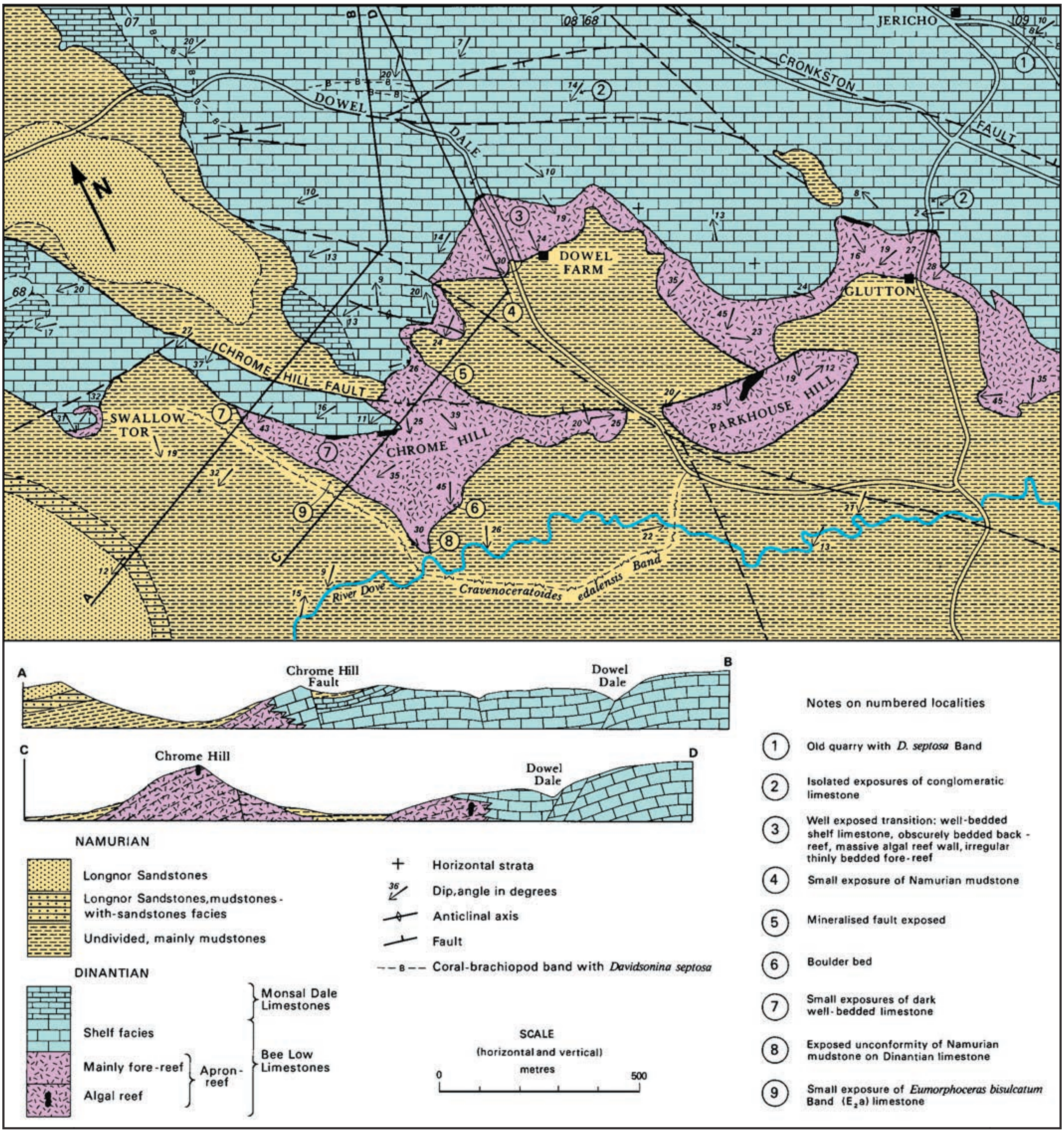
Opposite above: The geology of the reef limestones at Chrome Hill (after Aitkenhead et al., 1985).

Opposite below: View up the Dove valley with Chrome Hill in the centre and Parkhouse Hill to the right.

Left: Society members at the galena exposure on the Chrome Hill Fault.



Notes on numbered localities

①	Old quarry with *D. septosa* Band
②	Isolated exposures of conglomeratic limestone
③	Well exposed transition: well-bedded shelf limestone, obscurely bedded back-reef, massive algal reef wall, irregular thinly bedded fore-reef
④	Small exposure of Namurian mudstone
⑤	Mineralised fault exposed
⑥	Boulder bed
⑦	Small exposures of dark well-bedded limestone
⑧	Exposed unconformity of Namurian mudstone on Dinantian limestone
⑨	Small exposure of *Eumorphoceras bisulcatum* Band (E_2a) limestone

EXCURSION

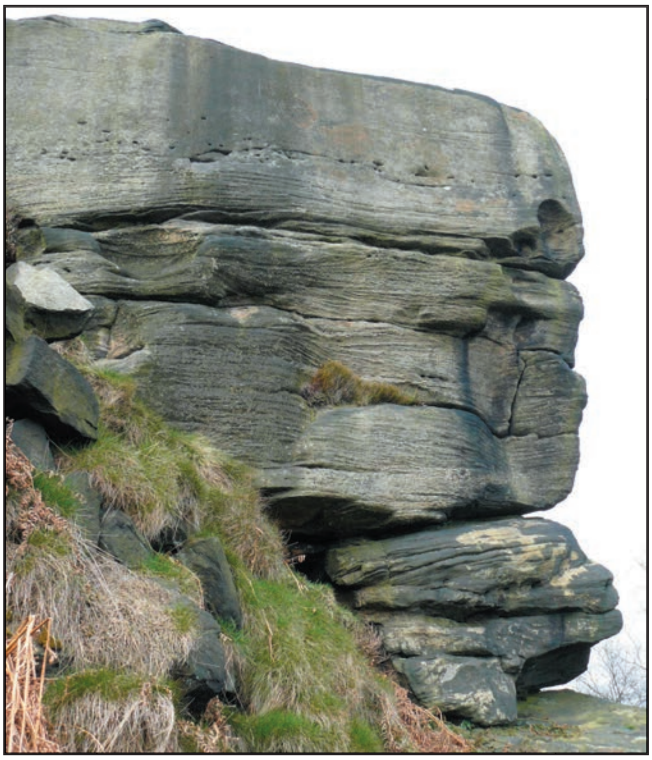
Ashover

Leader: Tim Colman

A dozen members took part in an evening walk, on Wednesday 6th July 2011, to visit the Carboniferous rocks of the Ashover area. These included limestones and volcanic ash of Carboniferous Limestone (Visean) age and sandstones and shales of Millstone Grit (Namurian) age. Ashover was an important centre for lead and fluorspar mining and also for stone quarrying, though all activity has now ceased.

The walk began through the village past the parish church, which has a lead-lined font dating from the 12th century, one of only thirty in the country. At the Poets' Corner Inn the path down Salter's Lane was taken towards Overton Hall. After crossing the River Amber, outcrops of dark grey Ashover Tuff with calcite veining occurr in the path, dipping westwards at a shallow angle. The volcanic centre was at Milltown about a kilometre to the southeast, down the Amber valley. Overton Hall was once the home of Sir Joseph Banks. Salters Lane was followed uphill past gently westerly dipping limestone outcrops, past Overton Hall and then onwards towards Cocking Tor.

The path crosses the Gregory Vein where galena, calcite, fluorite and sphalerite samples were found, as well as limestone and black shale as the host rocks. The Gregory Mine was a major lead producer in the late 18th century, with an annual output of over 1000 tons of lead; in 1772 the profits were over £15,000. The vein was mined over a distance of more than a kilometre under the gritstone escarpment; it was drained by a Newcomen steam engine and then the only Boulton and Watt engine to work in Derbyshire. The mine was abandoned in 1803, when the forehead was 300 m deep, due to water problems and the poor quality of the ore.



Ashover Grit at Cocking Tor.

Some of the party then took the steep track up to Cocking Tor, capped a large unjointed bedding surface in Ashover Grit that demonstrates why it was used for millstones. It was also an excellent viewpoint over the Gregory Vein tip and the Ashover anticline.

The party then returned to Ashover with a detour to inspect the old lime kilns below Hockley Quarry, which show an exposure of several metres of Ashover Tuff dipping eastwards on the eastern side of the anticline.

View down the old open-cuts and waste dumps left from the workings for lead in the Gregory Vein.

HOLIDAY GEOLOGY

Millom Rock Park

Millom is a small town situated on the Duddon Estuary in the southwest corner of Cumbria. It was built as a company town in the 1860s to serve the Hodbarrow iron ore mines. Initially ore was shipped to South Wales but later a steel works was built adjacent to the mines.

The ore was regarded as the richest source of hematite in the country; much of it was in the form of kidney ore with an iron content in excess of 60%, and samples from Hodbarrow can be seen in museum collections around the world. The orebodies in Carboniferous limestone extended out beyond the coastline, and ingress of the sea was a perennial problem for the mines, finally leading to closure of both the mines and the steel mill in 1968. At their peak more than 1000 men and boys worked underground and dividends were paid to the shareholders fortnightly. Over 25M tons of haematite were extracted during the mines 100-year life.

Since then economic activity around Millom has been much reduced, though quarrying for roadstone does provide useful economic activity. The flooded mine site is now split between the Hodbarrow RSPB bird reserve and a water-skiing centre, while the steel works site is now a nature reserve. Both sites are rich in orchids and are breeding sites for Natterjack toads.

A kilometre northeast from Millom, a fault brings Ordovician Borrowdale Volcanic rocks against the Carboniferous Limestone. These are lavas, tuffs and sills of the Millom Park Formation described by the BGS as "lapilli tuffs, mostly massive ignimbrites, some bedded ash fall tuffs with sills and irregular intrusions of basalt with andesite and rhyolite members". All have been metamorphosed, and so yield high-grade roadstone. The quarry is operated by Aggregate Industries Ltd who, together with partners, have created Millom Rock Park on a site overlooking the Ghyll Scaur quarry.

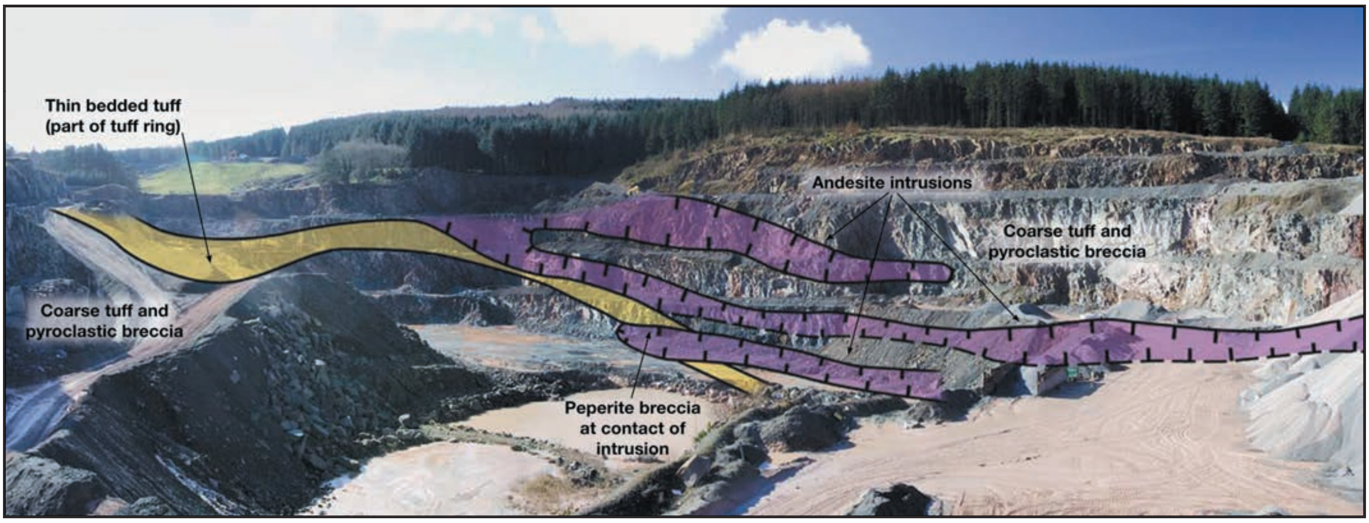

Cut face of a block of peperite breccia, with fragments of glassy andesite within a sediment matrix.

The Rock Park includes interpretation of the quarry workings and its products, together with a set of huge quarried boulders representing every rock type in Cumbria, each having its own interpretive notice board. A particularly helpful board pictures the quarry working face, showing the location of the three rocks exposed but are not easy to distinguish otherwise: the andesitic intrusions, coarse tuff and pyroclastic breccia, and peperite breccia; the latter was formed when lava flowed into wet sediments. Another board explains how after each day's blast an excavator is used to separate the three rock types; after milling and grading these are mixed to create the right aggregate for the final usage, which is mainly for surfacing motorways. All the interpretive notices for the quarry and its working are available at www.millomrockpark.org.uk .

This seldom-visited part of Cumbria is well worth a call. The Rock Park at SD176832 is not signed until its car park is reached. From Millom take the A5093 towards Barrow and Kendal, pass the quarry entrance, continue up to The Hill and turn left (signed School Ellis). The car park is shortly on the left. From the opposite direction, look for the sign to the right to School Ellis in the hamlet of The Hill.

Alan Filmer

The view into the quarry identifying the andesites that were intruded into the wet, unconsolidated pyroclastic sediments.



THE RECORD

Our membership now stands at 275 (and 31 institutional members), and we welcome new members who have joined the Society during the year until March 2012.

Indoor Meetings

In March the Annual General Meeting was followed by Barry Azzopardi talking about his work at Nottingham University on multiphase flow, with a laboratory-scale 'volcano' constructed to record infrasound and analyze the passage of gases through viscous liquids.

Also in March a joint meeting was held with the Yorkshire Geological Society at BGS Keyworth on the theme of 'Carbon Capture and Storage'.

This year's Members' Evening took place in April. Ian Thomas described how he had used his Churchill Fellowship in Scandinavia in 2009, exploring traditional building craft skills and materials, in the context of modern limitations. Richard Hamblin shared his experience of being caught up in the Christchurch earthquake in February. Being near the epicenter when it struck, he showed pictures of the effects of liquefaction and the damage to buildings and infrastructure. Katy Gosling reported on her undergraduate survey of the ostracod fauna of Groby Pool, Leicestershire, prompted by interest in living ostracods by Quaternary geologists. A scanning electron microscope aided identification and study of their anatomical features.

The new winter lectures opened in October with Prof. David Large of Nottingham University talking about how time might be measured in terms of coal deposits, and exploring the influence of massive volcanism.

In November, Colin Bagshaw gave an account of his visit to the Galapagos Islands. He demonstrated the impact of plate tectonics on their development and how the differences in the fauna of different islands had influenced Darwin's ideas concerning evolution.

Great stratigraphical myths were dispelled by Bill Bailey in December when he suggested that consideration of the gaps in the record led to understanding of some of its features and anomalies. This was followed by the Society's Annual Cheese and Wine social event.

The Devensian glaciation of the Vale of York was the subject of a lecture by Tony Cooper of BGS in January. He demonstrated how digital map data, digital terrain models, field mapping and borehole data enabled time slices to be constructed for the Vale's glaciation.

Tim Colman's final Foundation Lecture as President in February described Australia's mineral wealth and its mining history from exploration boom through to the present operations to secure iron ore, copper, uranium and gold in Western and Southern Australia. This was followed by the Society's Annual Dinner.

Field Meetings

May saw a day-visit to the Oxford area, led by Paul Sargent of the Oxford Geology Group. After a visit to Kirtlington Quarry with its Jurassic limestones and clays famous for mammal fossils, the afternoon was spent on a building stones walk around the Oxford colleges.

In June, Keith Ambrose took us to the Millstone Grit in Derbyshire to examine outcrops of the Ashover Grit and Rough Rock. Comparisons were made between the structure and lithology of each sandstone.

In July, an evening walk led by Tim Colman studied hydrothermal mineral deposits and mine workings in the Ashover area on a traverse across the anticline. Ashover had been an important site for mining lead and then fluorite.

A day excursion to Robin Hood's Stride in August was led by Gerry Shaw, relating the lithology of the Carboniferous rocks to landforms. Building stones and mining remnants were visited along the way.

The Upper Dove Valley was the focus of a visit led by Neil Aitkenhead in September. This examined the apron reef landforms of Parkhouse and Chrome Hills at the western margin of the Derbyshire Platform.

Also in September, a weekend excursion visited Shropshire. The Ironbridge Gorge Landslip Geotrail was walked on Saturday, followed by a visit, led by Andrew Jenkinson, to the fossiliferous Silurian Wenlock Limestone of Wenlock Edge. Devonian and Carboniferous sedimentary rocks and igneous intrusions of the Brown Clee area were visited on the Sunday.

Council

Our thanks go to the many members who are involved in the planning and leading of the field trips, without whom this important and enjoyable part of the Society's activities could not take place. We thank Sue Miles for editing the circular, Ian Sutton for the organizing the Field Excursions, and Richard Hamblin for managing the Lecture Programme.

The Society's website has been enhanced with an archive of back issues of Mercian Geologist, some from the earliest days of the Society and some more recent editions. Eventually all the back editions more than two years old will be available with free access, and preparation of the digital files continues. David Bate and the Editor are thanked for their work in making this possible, as is Rob Townsend for continuing to manage the website.

Council met formally on six occasions to discuss matters concerned with developing the Society for the benefit of its members and where possible to contribute to wider geological issues.

The Society's rock boxes for schools continue to be distributed. The contents of these are made up of rock, fossil and mineral specimens donated by individuals, organizations and institutions reducing their holdings. This year we are particularly grateful to the widow of the late John Aram, from whom we have received a large consignment of suitable specimens collected by John throughout his career. With his long association with geology in education we are sure he would be pleased to know that his specimens were being recycled in such a way.

Bantycock gypsum quarry, south of Newark

Above: grey massive gypsum from the Cocks Seam.
Right: the thirteen workable seams in the quarry face.
Below: pink and white alabastrine gypsum from nodules.

The quarry when dormant and flooded from 1993 to 2005. At water level, Triassic red Branscombe Mudstone with blocks of white gypsum. Above it, grey Blue Anchor dolomitic mudstone, fissile black Westbury mudstones, with grey Cotham mudstone at its top, beneath weathered Jurassic Scunthorpe Mudstone with limestones, capped by thin alluvium.