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East Midlands Geological Society

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Front cover: Pebble beds and current bedding in the Nottingham Castle Sandstone, exposed in the newly cleaned rock face beside the entrance to the Park Tunnel, Nottingham; see note on p.76. Photo: Tony Waltham.

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GEOBROWSER

Tsunami theory gains around Bristol

In April the BBC's *Timewatch* programme revealed details of a disastrous flood that inundated the northern and southern shorelines of the Bristol Channel and Severn Estuary. The events of the 30th January, 1607 (modern calendar date) have been pieced together by Simon Haslett (Bath Spa University) and Ted Bryant (University of Wollongong) from eyewitness accounts published in six pamphlets of the time. These all emphasised the suddenness and violence of the flood, which caused destruction on an unprecedented scale. But the accounts also provide evidence that a tsunami was the cause – for example, they say that the sea initially appeared to recede, before advancing as *'mighty hilles of water ….as if the greatest mountains in the world had overwhelmed lowe villages or marshy ground'.* Compare this with the sequence of events documented for the Asian tsunami of December 2004 reviewed elsewhere in this issue. In excess of 200 square miles of ground was devastated and at least 2000 people were killed, the flood waters penetrating up to 14 miles inland across the low-lying Somerset levels. The researchers estimate that the proposed tsunami wave height was probably less than 4 m in the Bristol Channel, but as it funnelled into the narrower reaches of the Severn estuary it increased to 5 m along the Glamorgan coast, and by the time it reached Monmouthshire it was over 7.5 m high and travelling faster than 60 kph *(Geoscientist, March 2005)*. Today, the affected coastal areas still bear the scars of the event – large blocks of rock that were ripped from the cliff are stacked in imbricate fashion above the normal high tide limit; there is evidence of farmland that had been rapidly scoured away; and there are new deposits of sand and mud with broken shell debris.

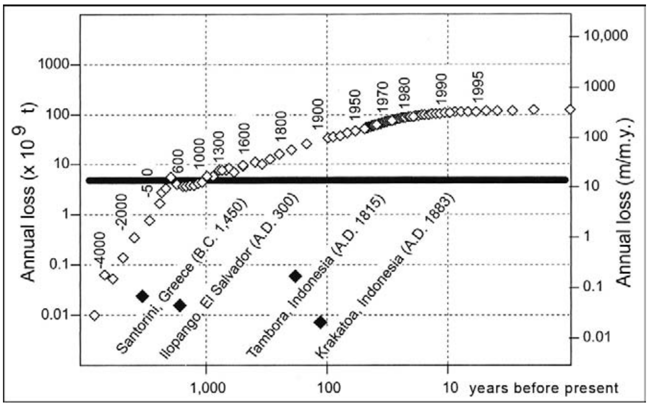
The only possible alternative explanation is that the flood was caused by a massive storm surge, but oceanographers acknowledge that this would require a combination of high tides and hurricane force winds, whereas contemporary accounts speak only of the weather *'being fayrely and brightly spread'* that morning. The answer to what caused the proposed tsunami presumably lies offshore, and the possibilities include a submarine landslide off the continental shelf between Ireland and Cornwall, or an earthquake that uplifted part of the seabed, or a combination of both with the earthquake as a trigger. Support for a seismic event comes from the fact that this area has experienced a number of earthquakes since measurements commenced last century, although with magnitudes not exceeding 4.5, these are admittedly small events. Moreover, the area lies along a major structure and potential line of weakness – the Variscan orogenic front – and geological maps of the sea floor between the Bristol Channel and southern Irish Sea show an abundance of faults available to cause a possible seabed rupture.

Canadian bonanza

A side issue of this year's election campaign has been the rise in petrol prices, which is in large part due to the production price of oil currently hovering at around US$55 per barrel. But this could be good news for the Anglo-Dutch multinational Shell because it could soon be reaping the benefits of a £2.5 billion investment in Canada, for the extraction of a fossil fuel that has lain idle for 40 years (*The Times, March 5, 2005*). The 'tar' sands of Athabasca, N. E. Alberta, constitute the world's largest hydrocarbon resource, but this sulphurous, dirty material had always been costly to exploit. Now, however, tar sands could be a far more attractive proposition than conventional oil reserves, thanks to recent technological advances that have lowered the current cost of extraction to only US$20 per barrel, with costs as little as $12-14 per barrel predicted for the future. The volume of tar sands deemed to be technologically retrievable today is 280-300Gb (billion barrels), even larger than Saudi Arabian oil reserves of about 240Gb. But the total reserves for Alberta, including oil not recoverable by current technology, are an amazing 1700-2500Gb. Most in situ bitumen and heavy oil production comes from reservoirs within Cretaceous to Tertiary strata buried more than 400 m down. The snag is that its extraction involves steam injection and there are environmental concerns, not least because these operations have the potential to liberate much carbon dioxide, one of the greenhouse gases implicated in global climate change. It seems likely that as the energy supply crisis begins to bite, and debate about supply versus pollution intensifies, the centre of world attention may well move from the Gulf to Canada.

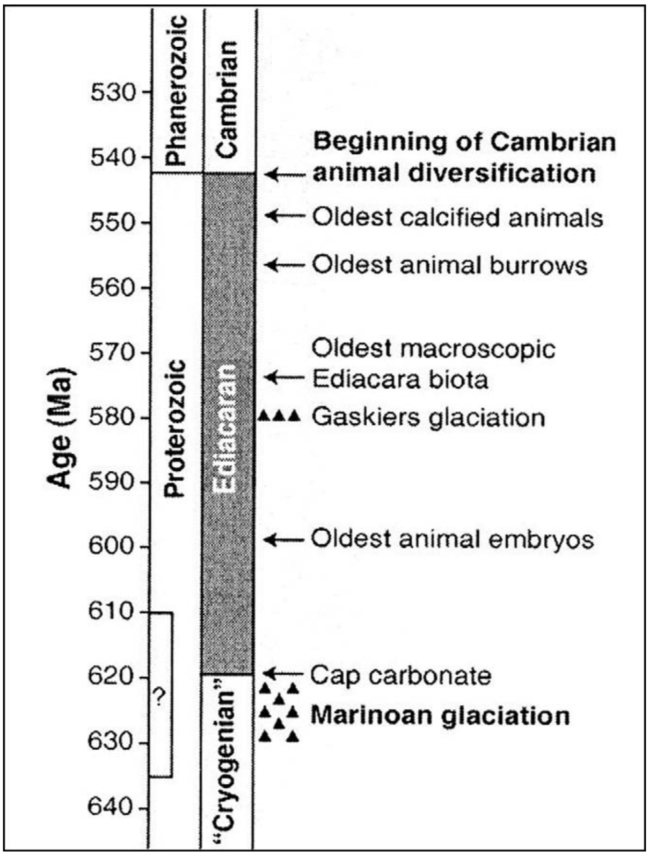
Humans have been at it again…

In the *Mercian* of 2001, Geobrowser reviewed evidence that humans are now the 'premier geomorphic agent sculpting the landscape'. The pioneering article in question (*Geology, 2000, p. 843*) was mainly concerned with the amount of earth moved by construction, but it also considered the huge volumes of material lost as a result of arable farming practices that have rendered vast areas vulnerable to soil erosion. Returning to this theme, an article in *Geology (2005, p.161)* estimates that soil loss from cropland agriculture actually accounts for 70% of the human denudation budget. This must be of some concern environmentally; therefore, the article asks, what is the rate of human denudation compared to natural erosional processes? Fortunately, estimations of the planet's natural, or 'deep-time baseline' erosion rate are now available, and when plotted against the rate of anthropogenic erosion it is apparent that the latter has predominated for the past 1000 years. To give one example of natural versus man-made forces, the current annual rate of human-induced rock and soil loss exceeds by 18,000 times the amount of material moved during the Krakatoa eruption. Nobody is



Historical rates of human-induced erosion (open diamonds) compared to large volcanic eruptions (closed diamonds), and to mean deep-time denudation rate of 24 m per million years (heavy black line). (From Geology, March 2005)

suggesting that all of the material shifted by humans necessarily leaves the land – a lot of it is 'stored' on the surface, or is washed as sediment into rivers that are incapable of conveying it any further towards the sea. What the calculations do show, however, is that a significant gap has opened up between the rate of 'erosion' mainly caused by current agricultural practices and that produced by the planet's own, sustainable, natural denudation regime.



A time-scale for the Ediacaran Period and the important biological markers that have been recognised within it. (From Science, v305, p621, July 2004, © AAAS)

Charnian rocks are now Ediacaran

Last year, in a major change of traditional practice, the International Union of Geological Sciences (IUGS) officially added a new subdivision to the geologic time scale for the Proterozoic (within the Precambrian) - the Ediacaran Period. As noted in *Science (p.621 July, 2004),* this is the first stratigraphically defined new period of any sort to be added since 1891 (when the USA's Carboniferous Period was subdivided into Mississippian and Pennsylvanian). It is named after the Ediacara Hills in Southern Australia, and its inauguration came after 15 years of deliberation and debate; but it disappointed Russian geologists, who wanted their own title of 'Vendian', first used in 1952, to be adopted. The Ediacaran is particularly significant and useful, however, because it is the first formally named Precambrian interval to be defined according to the principles that govern the Phanerozoic (post-Precambrian) time scale. In other words the top and base of the period, where they are preserved in a complete stratigraphical transition, are determined by events that have produced recognisable changes in the rock record, rather than by some (commonly) arbitrary age expressed in millions of years. For the base of the Ediacaran Period, the GSSP (Global Stratotype Section and Point), which is the 'standard' for recognising that datum worldwide, occurs in Australia at the base of a chemically distinctive 'Cap carbonate' bed. This bed overlies rocks deposited during a major worldwide glacial episode – known informally as the "Cryogenian Period". The absolute age of this lower datum is not precisely known, except that it is no younger than about 610 million years (Ma), and may be as old as about 635 Ma. The top of the Ediacaran Period is easier to define because it corresponds to the incoming of beds containing the first really diverse fossil assemblages, the forerunners to modern-day organisms. This 'evolutionary explosion' commenced at 543 Ma and it marked the demise of the unusual and still enigmatic Ediacaran macroscopic fossil biota, possible examples of which are featured elsewhere in this issue. The Charnian Supergroup is famous for these, and thus fits well into the Ediacaran Period; however, although such fossils characterise and actually lend their name to the period, they cannot be used to define its top and base because they are exceedingly rare. Perhaps the newly defined period will serve best as a time frame in which to place the development of organised Life before the Cambrian explosion. As shown here, the world's oldest animals currently date back to about 600 Ma, just above the base of the Ediacaran (*Precambrian Research, 2004, p.123*). To date, these have only been seen as microfossils, but it has been suggested (*Journal of Palaeontology, 2000, p.767*) that they are the embryos of cnidarians (which include jellyfish). Perhaps it is only a matter of time before the fully developed organisms are found as macrofossils and when this discovery is made, a lower rung will have been confirmed on the Ediacaran evolutionary ladder.

MERCIAN NEWS

Precambrian fossils from Charnwood Forest

Helen Boynton has made available new photographs of fossil impressions from the uppermost bedding plane on Ives Head, where strata of the Ives Head Formation (Blackbrook Group) are exposed. The locality, which is on private land at Lubcloud Farm, has been described by Boynton and Carney (2003); it is best viewed in morning sunlight.

The holotype of *Blackbrookia oaksi* is the only specimen found (see back cover), and shows a main branch on the left side, with lateral branches arising from it and decreasing in size towards the top; at the lower right hand side is a large circular disc with two thick, short branches arising from it. The holotype of *Ivesheadia lobata* (see back cover) contains a series of lobes within a roughly circular marginal rim that has small projections in certain places. A new specimen of *Shepshedia palmata* resembles a dog's paw print, with seven branches on its left side, two of which bifurcate (Fig. 1). A new variant of *S. palmata* was discovered in 2003 (Fig. 2); it has slightly thicker branches than the holotype (*Mercian*, 1995, p177), and these appear to dichotomise, arising from a central point near the top of the image.

These fossils have been the subject of previous work (Boynton, 1978; Boynton & Ford, 1995, 1996). They are by far the oldest macrofossils in Charnwood Forest, since they are from an horizon about 2000 m stratigraphically below the Ediacaran fauna seen at Bradgate Park, North Quarry (Charnwood Golf Club) and The Outwoods. The Ives Head assemblage is enigmatic; its relationship to the younger fauna, which includes the frondose forms *Charnia* and *Charniodiscus*, is not yet established.

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Boynton, H.E. and Ford, T.D. (1995) Ediacaran fossils from the Precambrian (Charnian Supergroup) of Charnwood Forest, Leicestershire, England. *Mercian Geologist*, **13**, 165-183.

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Park Tunnel

Within the last year, engineering works on the Victorian tunnel cut through bedrock in Nottingham' Park Estate have removed an unstable bed of the sandstone from the roof arch. Remedial work on the rock and stone walls at the Park portal of the Tunnel have included removal of much of the plant cover; so, until its ivy cover grows back, this splendid exposure of the sandstone is much improved (see front cover). The newly exposed small cave extends through to the rear face of the masonry above the far Tunnel portal.

Figure 1. *A new specimen of* Shepshedia palmata.

Figure 2. *The new variant of* Shepshedia palmata.

Nottingham's sandstone appreciated

A quote reliably attributed to a John Taylor in 1632 (source not known) - "If a man be destitute of a house, he has best to go to Nottingham, and with a mattock, a shovel, a chisel and a mallet he may play the mole and work himself a hole for him and his family."

Addendum

Two late additions to the Geology of Leicestershire bibliography in the last issue:

Copestake, P. & Johnson, B. 1989. The Hettangian to Toarcian (Lower Jurassic). 129-188 In Jenkins, D.G. & Murray J.W. (eds) *Stratigraphical Atlas of Fossil Foraminifera,* 2nd Edn. (Ellis Horwood: Chichester).

Chatwin, R. 1998. *The stratigraphy and geochemistry of the Liassic sediments at the Tilton railway cutting, Tilton on the Hill, Leicestershire.* Unpublished BSc Thesis, University of Leicester.

Erratum

An error occurred on page 40 of the last issue - the cave inside Castle Rock intersected by the Western Passages was a malt-kiln complex and not a tannery; apologies from the authors.

THE RECORD

Now embarked on its second 40 years, the Society has shown itself to be a flourishing organisation; membership now stands at 361, including 8 new members. Sadly the Society has been informed of the loss of three members namely Mr Bill Read, Mr Geoffrey Orme and Dr. Chris Salisbury.

The 2004 season of field meetings opened with an excursion to the Permo-Triassic of North Nottinghamshire led by Bob Toynton, its author in our East Midlands Guide. June saw evening visits to Stamford to study its building stones with Alan Dawn, and to the minerals of Ashover with Ian Sutton. The reef margins of Castleton were Gerry and Brenda Slavin's subject on a day trip in July. A weekend in the Yorkshire Dales with Tony Waltham was enjoyed in August, and the season finished with an excursion to the Charnwood quarries led by John Carney.

The programme of indoor lectures for 2004-5 started in March with the annual joint meeting with the Yorkshire Geol. Soc. at the BGS in Keyworth, when Geological Hazards and Disasters were covered in talks by Dr. Phil Allen and Dr. Nick Riley. In April, Dr. Clare Dudman threw light on the Life and Work of Alfred Wegener. As Chris Salisbury was unable to give his planned October lecture, Dr. Ian Sutton stepped in at short notice and spoke about the Volcanoes of the Inner Hebrides. The Building Stones of Northamptonshire were the subject of November's lecture by Dr. Diana Sutherland. Prior to the Christmas buffet, Dr. Tony Waltham shared with us his journey to the Afar Triangle in East Africa. In January, Ian Wall mixed geology and archaeology in his lecture on Ice Age art at Creswell Crags in January, and in his February Presidential Address Ian Thomas spoke of inspiring the young to be interested in geology.

Council met formally on six occasions to discuss a wide rage of topics aimed at improving benefits to the membership and promoting geology within the region. The East Midlands Field Guide has been a very successful publication; initial stocked have been sold and further supplies are being obtained to meet demand. Through collaboration with the Leicester Lit. & Phil. Society a guide to the building stones of Leicester will soon be published. A similar guide to the buildings of Nottingham is in this issue of the *Mercian*. Our journal marked the 40th anniversary of the Society, and continues to be sought after not only by members; the Secretary regularly receives requests for back numbers of the *Mercian Geologist*, for research purposes both in Britain and abroad.

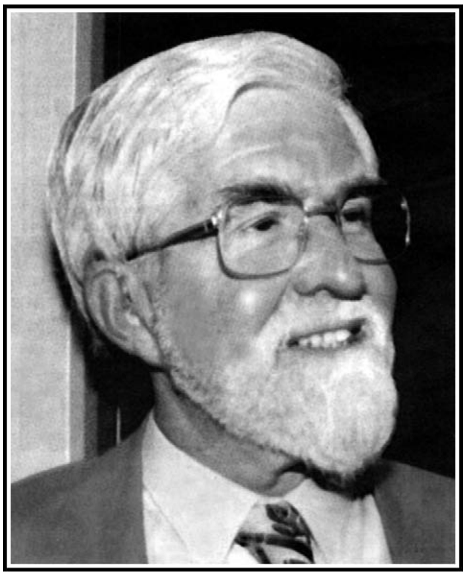
Once again, the Society's publicity stand was manned by members at a Creswell Crags special event weekend, and Alan Filmer conducted guided tours on both days. Council is always working to support geological projects, including this year the preservation of rock carvings in Nottingham's caves and also a publication on the local building stones (based upon Graham Lott's paper in the Mercian).

Janet Slatter, Secretary

VALE

Chris Salisbury 1929-2004

Chris was due to lecture to members of the Society in October 2004, but the event was postponed as he was unwell. Members were then saddened to hear of his death on November 27th, 2004.



A doctor and GP by profession, Chris was also a passionate amateur archaeologist. Retirement in 1992 allowed him extra time to pursue his interest in waterlogged wood found in the Trent Valley gravels. Taking every opportunity that arose to study the base of the gravels over a period 30 years, he found among other things, four medieval bridges, two Bronze Age log boats, a mill and many fish weirs. In the course of his researches, he became an expert on the geology of the base of the gravels and was able to add to the knowledge of the past meandering of the Trent. The waterlogged wood that he collected was used to set up the Tree Ring Dating Laboratory at the University of Nottingham. The Bronze Age log boat that he excavated was still carrying its cargo of Bromsgrove Sandstone for some construction project further downstream, and it revealed new information on the activities of the people of the time; the boat can now be seen in Derby Museum. (*Mercian*, v.14, p.104). Chris was responsible for the wonderful model of part of the Trent, showing the layout of the fish weirs he discovered, that was a centre piece of the now-closed Canal Museum in Nottingham. He was also an early promoter of the use of Nottingham's sandstone caves as a tourist site, and was involved in the current excavations under the Broad Marsh Centre.

Chris regularly attended Society indoor meetings, and members who talked to him will recall his amiable manner coupled with a scientific mind that enabled him often to ask perceptive questions of speakers, particularly if dating matters were discussed. He will be greatly missed, and the Society extends condolences to his widow, son and daughter.

FROM THE ARCHIVES

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

Rock Houses at Mansfield

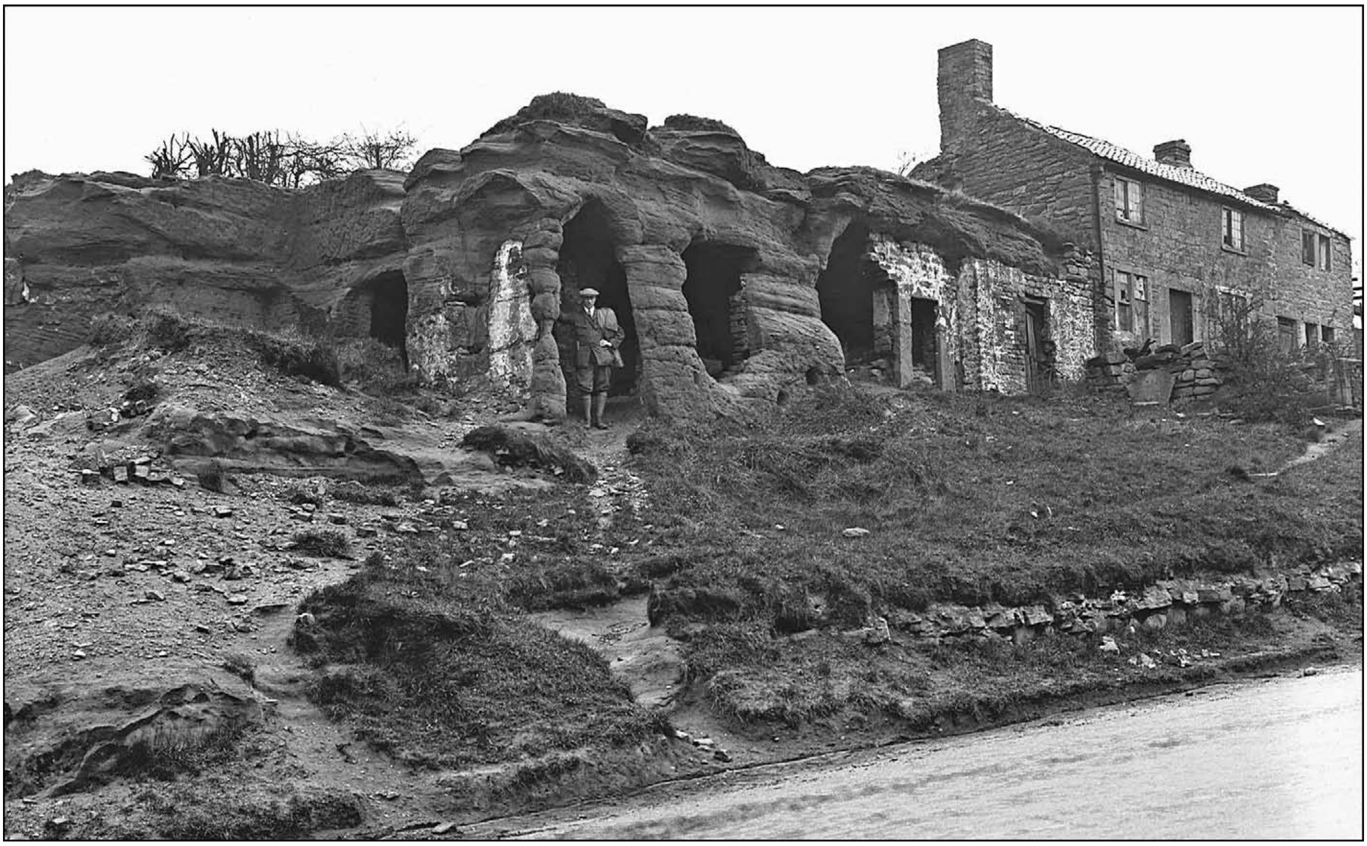
These old cave dwellings were recorded by the Geological Survey photographer Jack Rhodes in April 1911. The cave houses lie on the north side of Rock Hill, the main road from the centre of Mansfield onto the A617 to Southwell. They form part of a series of rock dwellings that were interspersed with conventional houses; those shown in the photograph lie towards the eastern, uphill, end of Rock Hill.

Like the caves of Nottingham, the Mansfield Rock Houses were hewn into the pebbly sandstone of the Nottingham Castle Sandstone Formation, formerly known as the Bunter Pebble Beds. As in Nottingham, the sandstone is friable and easily excavated, with widely spaced joints that enable cavity roofs to be self-supporting across substantial spans.

The original appearance of the rock houses at the western end of Rock Hill is well seen in a woodcut by J. Seddon Tyrer, dating from around 1868; this is on the website of the Old Mansfield Society at www.old-mansfield.org.uk/hudson1/hudson1f (which brings up a photograph of the western end of the Rock Houses dating from 1900, click again on the photo to bring up the earlier drawing). The cave houses consisted of a series of individual rectangular rooms interconnected by arched doorways. Front doors and windows were also cut into the rock, with at least part of the frontage faced with either local Magnesian Limestone or brick, and with wooden doors and window frames. Holes bored into the sandstone roof were surmounted by stone or brick chimneys to ventilate smoke from fires.

Similar rock houses in Nottingham, notably at Sneinton Hermitage, were excavated from the Middle Ages onwards until the 18th century. It is uncertain when the Mansfield Rock Houses were originally created, although the Old Mansfield Society's records (published as Bygone Mansfield by Linney in 1987) note that they too were in existence in the 18th century, and that the trade of besom-maker was traditionally associated with the occupants. One of the last recorded residents was a Mr Bramwell, although it would appear that he vacated his house some time before his death in 1900. The sandstone roofs, pillars and facing walls of the houses shown in this BGS photograph, and in the images dating from around 1900, are in a considerable state of collapse, and must have been abandoned well before those dates.

Andy Howard, British Geological Survey



The Mansfield Rock Houses in April 1911 (BGS photograph # A1156 © NERC).

Derbyshire Neck and Iodine Deficiency

Gerard Slavin

Abstract. Goitre and the associated neurological deficits of cretinism and deaf mutism due to iodine deficiency were common in Derbyshire, giving rise to the term *Derbyshire Neck*. These diseases were most prevalent in the 19th century and earlier, when they had devastating effects in the rural population. Since then they have declined in frequency. However, iodine deficiency disorders are still prevalent worldwide, and iodine deficiency is the single most common cause of mental retardation and brain damage. Globally, 2.2 billion people, ~38% of the world population, live in risk areas of iodine deficiency. Dietary iodine deficiency and environmental goitrogens block the synthesis of thyroid hormones. Iodine deficiency disorders are common in areas of low environmental iodine. But the iodine geochemical cycle is complex, and iodine deficiency disorders may develop in areas where iodine is present in the environment but is not bioavailable; this is because it is chemically bound in the soils, or because other dietary components inhibit the synthesis of thyroid hormones. In 19th century Derbyshire iodine deficiency diseases were likely to have been multifactorial. Goitres occurred principally in limestone areas and were due to the binding of iodine in the alkaline soils, with impaired uptake into local farm produce. Supplementary mechanisms may have included genetic susceptibility and dietary goitrogens. The decline of iodine deficiency diseases began with the increased standard of living and a wider range of dietary products from areas outside Derbyshire.

Goitres are clinically discernable enlargements of the thyroid gland in the neck and may arise from many diseases, from inflammation and tumours as well as compensatory enlargement of the gland. They occur sporadically, reflecting particular diseases of the thyroid in individuals, but also endemically, when a large proportion of a population is affected. In such areas, the high prevalence suggests causal environmental factors. Importantly, endemic goitre is accompanied in the population by a spectrum of catastrophic neurological defects including deaf mutism and cretinism. Endemic goitre is an ancient and world wide disease (Langer, 1960). The aphorism "*quis tumidum guttur miratur in Alpibus*" (who wonders at a swelling of the neck in the Alps?) is attributed to the poet Juvenal. Pliny the Elder (23-79AD), who died in the eruption of Vesuvius described goitres as occurring often in certain districts of Switzerland, and gave an early account of the belief, which persisted until the twentieth century, that this was due to water: *Guttur homini tantum et suibus intumescit, aquarum quae potantor plerumque vitio* (Swelling of the throat occurs only in men and swine, caused mainly by the water they drink). Mediaeval clinical descriptions of cretinism which emphasized the association with endemic goitre were those of Paracelsus (c.1527) and Platter (c.1562), who practiced in the Swiss or Austrian Alps (Sawin, 2001).

Goitre in Derbyshire

Derbyshire was an area of endemic goitre in the 18th and 19th Centuries. This gave rise, somewhat unfairly, to the term Derby(shire) Neck (Fig. 1), for there were other areas of Britain such as Yorkshire where it was similarly or more common. Indeed, Inglis (1838) commented that goitre in the Yorkshire Dales was as frequent as in the Swiss Alps. Early medical descriptions in Derbyshire give a flavour of the time both of social conditions and medical practice.

Prosser (1741) describes the lesion as observed and its frequency in one village: *The Bronchocele, or Derby-neck is a tumor arising on the fore part of the neck (Figure1). It generally first appears sometime betwixt the age of eight and twelve years, and continues gradually to increase for three, four or five*

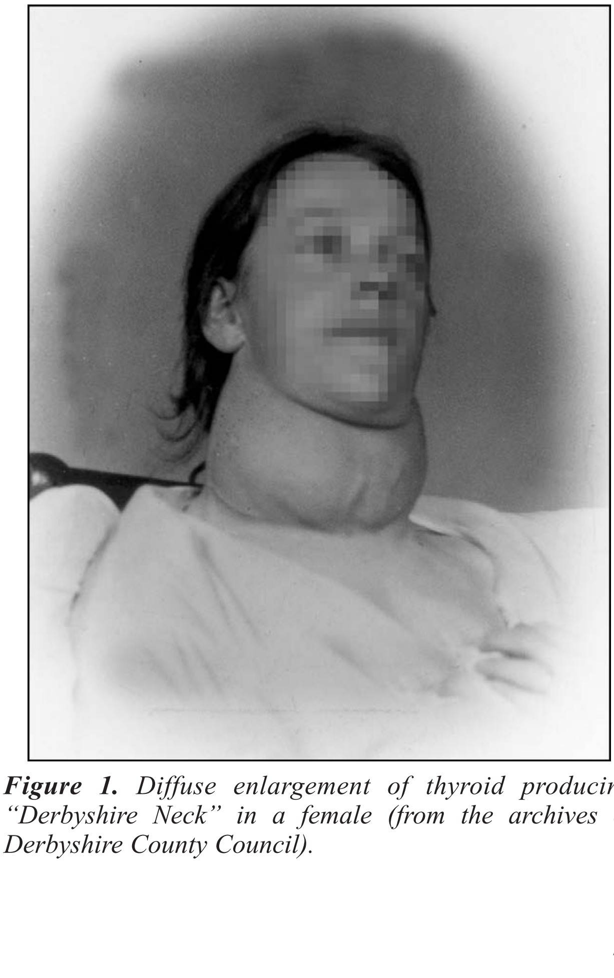


Figure 1. *Diffuse enlargement of thyroid producing "Derbyshire Neck" in a female (from the archives of Derbyshire County Council).*

years; and often the last half year of this time it grows more than it had for a year or two before. It generally occupies the whole front of the neck, as the whole thyroid gland is here generally enlarged, ... but is rather in the pendulous form, not unlike, as Albucasis says, the flap or dew-cap of a turkey-cocks neck, the bottom being generally the bigger part of the tumor and going gradually less upwards.... By the situation and nature of the complaint it occasions a difficult breathing, and very much so upon the patient`s taking cold, or attempting to run or walk fast. In some the tumor is so large , and so much affects their breathing as to occasion a loud wheezing.... .It is very common in many counties in England, Derbyshire especially, where from its frequency, it has the name Derby-neck .... .I have been informed by a gentleman of the faculty, from Duffield in Derbyshire, that there were near fifty poor girls afflicted with it in that small village.

Erasmus Darwin (1796), working as a medical practitioner in Lichfield, drew attention to water supplies as a possible cause of goitre: *Bronchocele. Swelled throat. An enlargement of the thyroid gland said to be frequent in mountainous countries, where river water is drank, which has its source from dissolving snows. This idea is a very ancient one ...The inferior people of Derby are much subject to this disease, but whether more so than other populous towns I can not determine; certain it is that they chiefly drink the water of the Derwent, which arises in a mountainous country, and is very frequently blackened as it passes through the morasses near its source; and is generally of a darker colour, and attended with whiter foam, than the Trent.*

A more vivid and compelling account of the disease and its disastrous social effects on affected families is given by Rev. D. Vawdrey, Rector of Darley Dale and vice-chairman of Bakewell Union in evidence to Parliament (British Parliamentary Papers 1968) and he made the important link between goitre and neurological deficits. *Goitre is an evil incident to this locality, so extensive and so mischievous that no report of the districts of Derbyshire would be complete without some reference to it. There is a great deal of it in this parish. In one family six daughters were deaf and dumb, one son a maniac, and another imbecile. In another family four daughters were deaf and dumb. There are many other cases of imbecility and imperfect development either of bodily or mental power or both, all in this parish. Yet this parish is well drained, has admirable water all flowing from gritstone and is spread over a wide and very open valley. Goitre chiefly prevails among the aboriginal inhabitants. I know but of one instance where any strangers coming to live here (and there are many) have shown any symptoms of it. Among the aborigines the system of intermarrying has been carried on for generations to an extent which I have never met with out of Derbyshire and to this fact more than any other, I attribute the prevalence of this disease* (in fact the western half of the parish is underlain by limestone, and much more has calcareous soils on the limestone-rich till). At the same hearing, Mr C. Evans (British Parliamentary Papers 1968) noted significantly that *Cases of 'Derbyshire neck' are diminishing though still hanging about the districts in which it used to prevail.*

Dr William Webb (1886), a physician and surgeon of Wirksworth for thirty years, emphasized the association of goitre and cretinism (Fig. 2), but gave further insight into the changing frequency of the disease and into life for working women then. He had an eye for the rocks and water sources as possible aetiological factors: *goitre is a true hypertrophy of the thyroid gland from the excessive performance of functional duty. This theory explains to some extent the occurrence of bronchocele when the girl is approaching womanhood; and also those cases which happen in women who get their bread as workers in the cotton mills of Derbyshire and who have frequently to walk two, three or even four miles, over steep hills to their work before six-o-clock in the morning; then to live in a flocculent atmosphere, working all the time, for ten hours a day and afterwards to tramp over the same ground at night. .... Enlargement of the thyroid gland is for the most part seen in women belonging to the working classes, although not altogether confined to them. It is also common in those whose ancestors have intermarried. .... It is found equally amongst the Yoredale rocks and limestone formations, and does not appear to be confined to those who drink any special character of water. .... It is much less prevalent now than it was thirty years ago and yet women drink the same waters. They get better wages, which means better and more nutritious food. The railway communication which did not then connect the goitrous districts with the county town has now given the people opportunities and means to pay visits to other parts of which they constantly avail themselves;*

Figure 2. *Two 19th century cretins from Derbyshire. "I have a family in my recollection at this moment, consisting of a man and his wife (since dead) having a large fibrous goitre. Both are of average mental capacity. They have some sharp children and also two cretin women their offspring. These latter, in age between 20 and 35, are stunted in growth and have but limited powers of understanding or even of going to and fro, except in the shuffling gait of the paralytic. They sit from morning till night, nursing a doll, or other toy and comporting themselves as very little children do, but with only a fractional part of their intelligence". (from Webb, 1886).*

consequently there has been less intermarriage and less breeding in-and-in; and I am decidedly of the opinion that, if the decrease of bronchocele take place in the same ratio as it has done in the last generation, ere another has passed away, endemic goiter will, so far as Derbyshire is concerned, have almost disappeared.

Goitre was, thus, widely recognized in Derbyshire in the 18th and 19th centuries in anecdotal accounts, but the wider pattern of associated diseases was also seen as a problem by physicians and politicians alike.

Towards an understanding

The first systematic study of goitre in England and Wales (Berry, 1891) delineated a high frequency goitre belt extending from Cornwall, through Somerset, Oxfordshire and the Midlands to Derbyshire and the northern Pennines, with offshoots into North and South Wales (Fig. 3). Berry described the Carboniferous limestone areas of England as the very hot bed of goitre, and recorded particularly numerous sufferers in Cromford, Matlock, Youlgreave, Bakewell, Baslow and Stoney Middleton. Stocks (1927) surveyed the prevalence of goitre in 375,000 schoolchildren throughout England and Wales, confirming the distribution of goitre and the high rates in limestone areas. Turton (1933) studied the prevalence of goitre in Derbyshire, and noted that it was not confined to but was much more prevalent in limestone areas. Significantly, he noted that by then cretins had become a rarity.

The Goitre Subcommittee of the Medical Research Council (1944) estimated that in England and Wales there were 500,000 cases of thyroid enlargement in persons between the ages of 5 and 20 years. Kelly and Snedden (1958, 1960) commented that there was no reason to suppose any lessening of the figure in the intervening years. However, a survey by general practitioners of thyroid abnormalities in the Peak District (West Derbyshire Medical Society, 1966) showed a large decrease in thyroid abnormalities in younger people but without a comparable decrease in adults; this provoked them to write that the time had not yet come to forecast the imminent passing of Derbyshire neck and led to the increased recommendation of iodised salt to younger families in their care. Nevertheless they observed: *a lower consumption of locally grown produce began with the railway penetration of the Derbyshire valleys near the turn of the last century and one of the older practitioners used to say this coincided with a fall in the local prevalence of goitre even then.*

In conclusion, the natural history of goitre and its associated disorders in Derbyshire was that its prevalence in the 19th was severe, affecting whole communities, but that it slowly declined in severity. This decline preceded any specific treatment for iodine deficiency, with the opening of rural areas to the wider world by better communications, importation of dietary products from outside Derbyshire and improved living standards. Goitre persisted until the middle years of the 20th century, despite the introduction of iodine prophylaxis. A similar progression in other limestone districts has been observed, as at Hooke Norton in Oxfordshire (on Jurassic limestone), where iodine deficiency persisted in school children until the 1950s (Hughes *et al*, 1959).

Iodine deficiency in goitre

Numerous ancient treatments for goitre included seaweed extracts, and iodine was discovered in burnt seaweed residues by the French chemist Courtois in 1811. Coindet, an Edinburgh-trained physician, gave potassium iodide to goitrous patients in Geneva in 1820 with great success. However, others gave iodide in a grossly high dosage; the induced side effect of thyrotoxicosis caused fatalities, and the treatment largely fell into disrepute (Langer, 1960). At the end of the 19th century, fried sheep thyroid or dried thyroid extract was used successfully in the therapy of hypothyroidism, and in the search for the active principal, iodine was found in the gland. The active hormone thyroxin was identified and named by Kendall in 1919. It was synthetised by Harrington and renamed thyroxine (T4), a more chemically correct name, for it is an amino-acid derivative with four iodine atoms rather than an indole structure as Kendall believed. Subsequently a second hormone triiodothyronine (T3) was found.

Marine (1920) re-established the therapeutic and prophylactic use of iodine in a report on the prevention

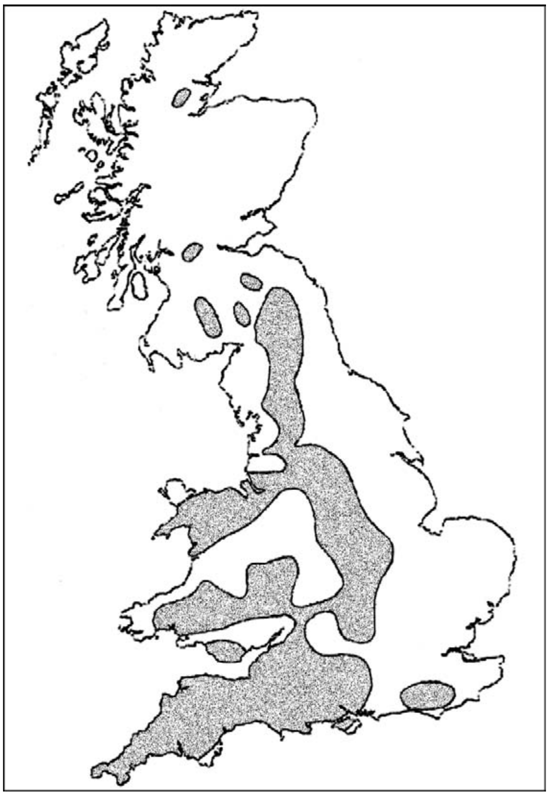


Figure 3. *Goitre distribution in Great Britain, recognized by Berry (1891), with much of the main goitre belt (shaded), underlain by carbonates.*

of simple goitre in schoolgirls in Akron, Ohio. However, his view of endemic goitre as an iodine deficiency disease was not without opposition. The long-established view was that endemic goitre was due to something in the water supplies - toxins, bacteria or parasites (McCarrison, 1906; Berry, 1891) rather than iodine deficiency; this view prevailed for some time and with contention. Turton (1933), working in Derbyshire, produced experimental evidence purporting to show that endemic goitre was not related to iodine deficiency and concluded there was no case for the *promiscuous administration of iodine amongst either the children or adults of this county*.

Nevertheless, opinion changed, and following Stocks` survey (1927), a recommendation was made for the prophylactic administration of iodine to girls in endemic areas of England and Wales, but was never implemented. During the 1939-45 war, concern at the prevalence of goitre in women munitions workers prompted the Medical Research Council to appoint a Goitre Subcommittee (1944). They recommended the general adoption of iodised salt throughout the country, but no government action followed, except that iodide was added to the vitamin tablets issued to expectant and nursing mothers. Iodised salt became commercially available in Britain in the immediate post-war years through the initiative of Cerebos. Iodised salt was custom-packed for various Cooperative Society stores, but the last supplied were in the Derbyshire area.

Sources of iodine in the diet

The recommended adult daily intake of iodine is about 100-150 µg/day (Hetzl, 2000). Fish and seafood is a major source of dietary iodine, and is forty times richer than most other foodstuffs (Johnson *et al*, 2003). Arable crops and vegetables are not rich in iodine, and inland areas far from the marine source may provide only low amounts of iodine. Leafy vegetables and grass concentrate iodine by adsorption on the leaves from the atmosphere. Iodine may then enter the diet through animal products, especially those of grazing animals; these secondarily concentrate iodine, by ingesting not only grass and leaves but also soil, which includes soil-bound iodine not bioavailable through plants. In today's developed countries, a major source of iodine lies in dairy products because of the addition of iodine to cattle feed and the use of iodine containing disinfectants in cattle sheds. Iodised salt is a potentially important source, but its use is not mandatory and much on our shops is not iodinated.

In the past, surface water supplies were emphasized as an important source of dietary iodine, but water sources are likely to supply less than 10% of daily dietary requirements. Inhalation of atmospheric iodine is possible but with a minor input of only 0.5 µg/day.

Pathophysiology of the thyroid

The thyroid gland lies in front of the trachea in the neck. Its principal function is to secrete iodine-containing hormones. This depends on an adequate iodine supply and uptake by the thyroid, on hormone synthesis and release from the gland. Geochemical or dietary agents may interfere at different stages, producing a primary lack of iodine in the diet, inhibition of hormone synthesis or alterations in hormone usage.

- *Iodine concentration in the thyroid*. Iodide is absorbed from the gut and circulates by the blood to the thyroid where it is concentrated to maintain an iodine gradient of 100:1 between the thyroid cell and the blood. In iodine deficient conditions the gradient may rise to > 400:1 to keep the required daily intake.
- *Synthesis and release of thyroid hormones*. Iodide is oxidized to either nascent iodine or I_3 which combine rapidly with tyrosine, to form mono- and di-iodotyrosine and these are coupled to form the thyroid hormones, thyroxine containing 4 iodine atoms (T4) and tri-iodothyronine containing 3 iodine atoms (T3).
- *Peripheral action of thyroid hormones*. T4 and T3 are released into the blood and carried to the tissues. There they maintain cellular metabolism at a basal rate. In addition to these actions, the hormones have important effects on the growth and development of the brain in the foetus and new-born. Therein lies the major importance of iodine deficiency disorders.

Foetal and neonatal brain development is characterized by two main periods of growth. The first is between the third and fifth months of pregnancy when there is nerve cell proliferation and initial organization of the nervous system. The second occurs in the third trimester and continues into the second and third years of post-natal life. Thyroid hormones co-ordinate and regulate growth through binding of T3 to nerve cells in different parts of the brain. During the initial phase of growth the supply of thyroid hormones to the foetus is almost entirely maternal. T3 bound to foetal nerve cells is produced by the foetus from circulating maternal T4. Foetal synthesis of T3 from maternal T4 is of particular importance in those areas where there is a combined deficiency of selenium and iodine (see below), when it is a factor in determining the clinical type of cretinism (Delange, 2000).

Control of thyroid function

The activity of the thyroid gland is controlled by a feedback mechanism: low levels of thyroid hormones induce secretion of thyroid stimulating hormone (TSH) from the pituitary gland. There is then an increase in the number, size and functional capacity of thyroid cells with increased synthesis and release of thyroid hormones from an enlarged thyroid - a goitre.

Enhanced physiological TSH secretion occurs at particular times of need such as adolescence, in girls at the menarche and in pregnancy. In these groups, even on an adequate diet, slight thyroid enlargement may be seen. In some cultures, mild thyroid enlargement and enhanced delicate curve of the neck in young women is seen as a sign of beauty. During the Renaissance, goitre was a common feature in Italian paintings of the

Madonna. In the context of endemic goitre, any environmental factor interfering with thyroid hormone synthesis or function results in thyroid stimulation from the pituitary and pathological enlargement.

Clinical effects of iodine lack

Thyroid enlargement in an individual may cause symptoms (Fig. 1), but this is rarely a major public health problem. However, endemic goitre is a marker for important associated syndromes arising from maternal thyroid hormone deficiency in pregnancy, including infertility, abortions and stillbirths, endemic cretinism and impaired mental capacities in children and adults. The whole spectrum of disorders is better termed iodine deficiency disorders (IDD).

There are two polar forms of endemic cretinism - the neurological and the myxoedematous types (McCarrison, 1908) though many are intermediate in presentation. These forms relate to the timing of the maximal hormonal deficiency insult to the child`s development, whether early in pregnancy or in the neonatal period (Stewart & Pharoah, 1996). Neurologic cretinism is characterized by severe mental deficiency, deaf mutism and spastic paralysis. The myxoedematous form shows mental deficiency with short stature and markedly delayed sexual and bone maturation. The skin and other tissues may be thickened by a mucinous deposit which gives rise to the term “myxoedematous” An associated deficiency of selenium in a geographical area is a factor in the predominance of myxoedematous cretinism in that location (Delange, 2000).

Importantly, studies in at-risk populations indicate that cretinism is not an all-or-none phenomenon and that iodine deficiency has wider neural effects than the classical forms. Associated with endemic cretinism, increased numbers in the “normal” population have motor and cognitive deficits. Any neural damage to the brain is permanent, and eradication of iodine deficiency is therefore a critical public health matter.

Selenium deficiency

A new development in the understanding of iodine deficiency diseases is the recognition of combined iodine and selenium deficiencies (Delange, 2000). Selenium is an element closely allied in chemical and physical properties with sulphur, and occurs as a trace element with a concentration of ~0.05 ppm in continental crust. In the thyroid it is a component of enzymes that scavenge free radicals. These are chemical species that are continuously produced in cell metabolism and are chemically active, with great potential to damage the cell by oxidation. unless constrained by antioxidant mechanisms.

In Zaire, myxoedematous cretinism is the predominant form rather than the neurological form and is found in areas that are severely iodine deficient but which are also deficient in selenium. The selenium deficiency may act in two ways:

- Iodine deficiency produces thyroid stimulation through pituitary feedback with increased synthesis of free radicals in thyroid cells. An associated selenium deficiency causes a lack of scavenging enzymes within the thyroid, which is then more sensitive to oxidative stress and thyroid function is further impaired.
- Selenium is also a component of enzymes responsible for the conversion of T4 to T3 in tissues and deficiency of this enzyme produces decreased breakdown of T4. In a pregnant woman, the selenium deficiency prevents the development of neurologic cretinism by increasing the availability of maternal T4 to the foetus during the first trimester. The myxoedematous form develops due to iodine deficiency in later pregnancy and the neonatal period when the child depends on its own deficient production of thyroid hormones.

Genetic factors

Genetic susceptibility plays a role in the development of IDD. In the western Sudan, family studies show a significantly higher incidence of endemic goitre among the offspring of affected parents than among those of normal parents (Bayouni *et al*, 1988). Held *et al* (1990) studied 70 families afflicted with endemic cretinism in highland Ecuador where an autosomal recessive genetic predisposition is a major factor. In each of three iodine-deficient areas in central China, where neurologic cretinism is common, Wang *et al* (2000) studied the expression of genes which affect thyroid hormone binding to nerve cells, and altering their effects on growing nerve cells. In each area, the genes were significantly more common in affected children than in normal controls.

Goitrogens

Iodine and selenium are geochemical goitrogens whose effect on thyroid function is produced by deficient intake. There are other naturally occurring vegetable goitrogens which produce an effect through positive interference with thyroid function either by inhibiting iodine uptake or hormonal synthesis. They have an additive effect to iodine deficiency, and this is seen if the iodine intake is marginally limited and/or the goitrogen intake is prolonged. Their effects may be severe and their influence is seen in endemic areas.

Thiocyanates and isothiocyanates are goitrogenic and act by blocking transport of iodine into the thyroid. They or their precursors are found in staple foods such as cassava, maize, and bamboo shoots in Third World countries. Cassava, a staple in Zaire, is thought to be an adjunct in the cause of endemic goitre and cretinism due to the release of thiocyanate from a cyanogenic precursor in the tuberose root. Thiocyanates occur in pearl millet a staple food in endemic goitre areas of western Sudan. Pearl millet is rich in flavenoids, a group of polyhydroxyphenols, that are metabolized by intestinal bacteria to compounds which inhibit not only enzymes involved in thyroid hormone synthesis but also those involved in their peripheral metabolism (Engel & Lamm, 2003).

Geological contexts of IDD

At present, iodine deficiency diseases affect more than 740 million people, 13% of the world population, and another 30% are at risk. Nearly 50 million people suffer from some degree of IDD-related brain damage, ranging from cretinism to a lowered intellectual ability (WHO, 2003)

Areas with a high prevalence of goitre show no single unifying geographical or geological feature but certain patterns of distribution occur. Many are in high mountains, including the Alps, Himalayas and Andes and their subsidiary chains. Other areas are at sea level, such as the Netherlands, the Indo-Gangetic plain and coastal Sri Lanka. Areas with water supplies percolating through a limestone source are also at risk; these include the Appalachians, Ecuador and the limestone areas of Britain (Kelly & Snedden, 1958).

In Zaire, there is a significant contrast in goitre prevalence on Idjwi Island in Lake Kivu (Delange *et al*, 1972). The northern part of the island, with a high goitre rate, has granitic and gneiss bedrock; the southern part is non-goitrous and has a basaltic bedrock. The difference in goitre rates may in part be due to dietary goitrogens, but similar contrasts over corresponding bed rocks have been described from Nigeria (Wilson, 1954). An increase in goitre over the granite batholith was formerly seen in S.W. England, but the iodine deficiency was ascribed to iodine binding by the overlying peaty soil (Fuge, 1996).

A large contrast in goitre prevalence has been noted between populations living on either side of the main Karakorum thrust, the western continuation of the Indus-Tsangpo suture line in northeastern Pakistan (Stewart, 1990; Stewart & Pharaoh, 1996). Though both areas were iodine deficient, goitre was more prevalent on the northern Asian plate than on the southern Indian plate. Similar goitre endemias occur in other convergent zones in Indonesia, New Guinea, the Andes, Alps and Pyrenees. Stewart initially speculated that subduction of the Indian plate concentrated metallic goitrogens such as lithium, boron and molybdate in the Asian plate through melting and metamorphism. Subsequently, Huh and Stewart (2003) found significant differences in the iodine concentrations between streams draining the Karakoram metamorphic complex north of the thrust and those draining the Kohistan-Ladakh island arc south of the thrust. They concluded that, in this area, lithology and tectonic processes were more important than atmospheric transport and deposition of iodine.

Almost no country is free from the risk of iodine deficiency disorders, but some are now goitre free due to prophylactic iodination measures. The risk of these disorders is now chiefly, but not entirely (Nohr *et al*, 1993), in poor, isolated and underdeveloped areas of the world, especially if they are dependant for their diet on local produce.

Goitre in calcium-rich environments

Goitre, long recognized in limestone areas suggested a direct role for calcium as a goitrogen (McCarrison, R., 1926). In experimental studies this was ascribed to water hardness (Taylor,1954) but Harrison et al (1967) showed no effect of calcium on iodine metabolism in man. In Nepal, Day and Powell Jackson, (1972) found that goitre prevalence correlated not only with the hardness of the water but also with its fluoride content. In limestone areas, rather than calcium acting on the thyroid directly, its presence alters the chemical environment of the soil, and therefore acts indirectly on the mobility and distribution of other elements.

Environmental sources of iodine

A traditional explanation for dietary iodine deficiency is that it is due to soil depletion following intense glaciation, where iodine is stripped from the soils, then carried by rivers to the sea with failure of replenishment, leaving a low iodine environment and consequent dietary deficiency (Goldschmidt, 1954; Kelley & Snedden, 1958). There is little evidence to support this. There is no major difference between the iodine content of soils in areas of recent glaciation and

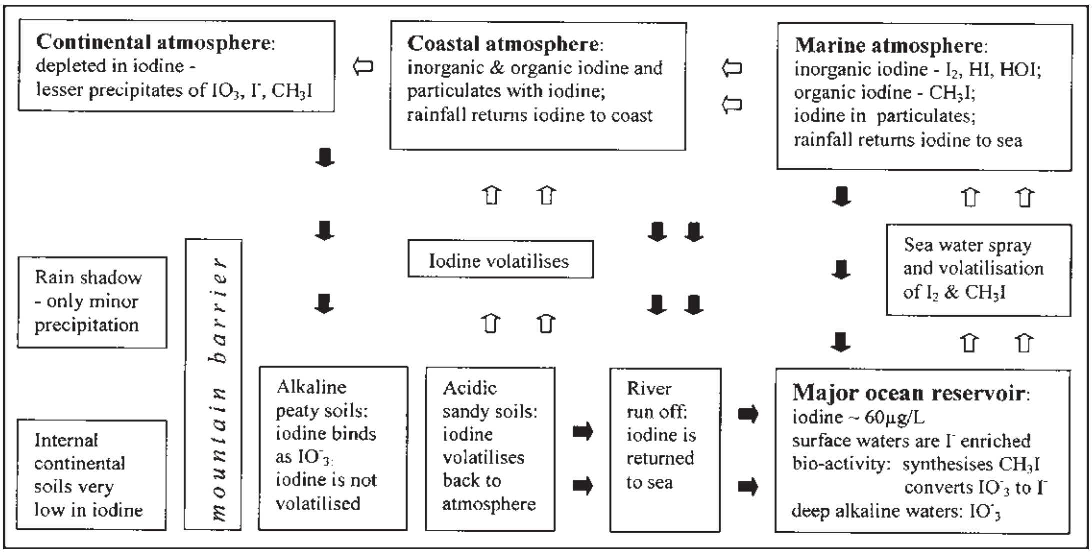


Figure 4. *Migration of iodine between the marine and terrestrial environments.*

those in non-glaciated but similar geographical locations (Fuge, 1987). Young glacial soils re-equilibrate with their surrounds rapidly rather than in thousands of years (Fuge and Johnson, 1986; Johnson *et al* 2002). Persistent low iodine contents of soil in glaciated areas reflect either their geographical location with a low iodine input at altitude and in rain shadows, or an inability of the soil to bind iodine.

Nevertheless, at least in much medical literature, there is an implicit assumption that iodine deficiency diseases are primarily due to low levels of environmental iodine producing a low iodine dietary intake; the assumption is buttressed by the apparent success of iodisation programmes. This emphasises the dietary deficiency of iodine, but it underestimates the complexity of the geochemical cycle of iodine and its interactions with biological processes that produce the deficiency. There is little recognition that soil iodine may not be bioavailable or that geochemical as well as dietary factors may act as goitrogens (Stewart, 1990, Stewart & Pharoah, 1996).

Lack of iodine in surface waters is sometimes a marker of a goitrogenic risk due to low levels of iodine in the environment, as in the Himalayas and rain shadow areas of British Columbia. Here iodine levels in surface waters are less than 1.0 µg/l (Day & Powell-Jackson, 1972; Fuge, 1987) and both are areas of severe endemic goitre. Water supplies have been classed as goitrogenic if they contain less than 3-5 µg/l iodine (McClendon & Williams, 1923). However, iodine levels in surface waters do not always correlate with the presence or absence of goitre. In an analysis of surface waters, the highest values occurred in Missouri and Derbyshire, both areas of endemic goitre and both draining limestones (Fuge,1989). Mean iodine level for surface waters in an area without history of IDD in mid-Wales are ~2.11 µg/l, and this is lower than the ~3.94 µg/l in affected areas of Derbyshire (Fuge, 1989). The iodine content of surface waters is very variable, but is usually less than 15 µg/l. The variability depends not only on the nearness to the seawater source and on precipitation, but also on run-off from recent marine sediments. Effluent contamination from mines and agriculture may also affect levels, as does recycling of domestic supplies, as in London which has high iodine levels (Fuge, 1989).

There is no consistent relationship between levels of environmental iodine and endemic goitre. In a study of the distribution of environmental iodine (atmospheric deposition, soil and surface water content) in England and Wales, related to the goitre belt delineated by Stocks (1927) there was no correlation between the distribution of iodine and the presence or absence of endemic goitre (Stewart *et al.*, 2003). Similarly in Sri Lanka iodine contents of soil and water do not correlate strongly with goitre endemicity (Dissanayake & Chandrajith, 1996). Besides absolute low levels of environmental iodine, other mechanisms which inhibit iodine bioavailability have to be sought and the solution to this lies in the iodine geochemical cycle.

Geochemical cycle of iodine

Iodide has a large ionic radius (220 pm), so does not fit easily into crystal lattices and is therefore not generally found in rock-forming minerals. Its concentration in igneous and metamorphic rocks is ~0.25 ppm. There is a greater range in sedimentary rocks, with a higher content in claystones than sandstones; highest values occur in organic-rich shales, with concentrations in bituminous shales up to 44 ppm. The content in limestones is variable and correlates with organic content (Fuge, 2005).

Seawater is the principal reservoir of iodine, where it exists in several forms. Inorganic iodine is present as iodide and iodate anions, with an increased proportion of iodide present in near-coastal waters due to bio-conversion of iodate to iodide. Organic iodine compounds include the volatile methyl iodide, which may be formed biologically by seaweeds and phytoplankton. Organic compounds may constitute nearly half the iodine content in coastal waters.

Iodine is transferred from the ocean to the atmosphere, some as spray and aerosols, but most by volatilization of iodine species. Seawater iodide anions are converted to elemental iodine and volatilized by photochemical oxidation. Volatile organic iodine compounds have been identified as the predominant source of atmospheric iodine in Japan and Europe, and methyl iodide is suggested as a long distance atmospheric iodine transporter (Heumann *et al*, 1990)

Iodine is transferred from the atmosphere to the terrestrial environment by precipitation, with iodine deposition decreasing with distance from the sea. Iodide anions are the principal deposit, with prior conversion of atmospheric iodate to iodide and organic iodines to iodine by photolysis. Fuge (1996) envisaged that marine derived iodine is deposited in a near coastal environment and that it is revolatilised secondarily from the soils and carried in the atmosphere to more inland areas in a series of repeated migratory steps. These steps are subject to blocking at any stage by geochemical barriers such as organic-rich or alkaline soils that increase iodide binding and inhibit further inland migration (Fig. 4).

The iodine content of soils varies over a range of <0.1 to >100 ppm. Soils in coastal areas are enriched in iodine compared to those more distant from the sea; soils in continental interiors and in mountain rain shadows may have very low levels. Variability depends not only on the supply rate of iodine but also on the ability of the soil to fix and retain iodine. Soils are generally richer in iodine than their subjacent parent rocks because most iodine in soils is derived through the ocean-atmosphere link, and relatively little is added by weathering of bedrocks that are low in iodine. However, the parent material may control the amount of iodine in the overlying soil by its ability to bind iodine. The large number of interrelated soil characteristics that affect binding contribute to a simple model (Fig. 5) of the iodine fixation potential of soils (Fuge & Johnson, 1986; Fuge,2005).

Iodine is added to soils by precipitation as iodide and iodate anions. There they are primarily absorbed by clays, iron and aluminium oxides and especially by organic matter such as peat. If some of the iodine remains unbound because of a paucity of binding sites, it persists in a mobile form and is available for revolatilisation, but the amount available also depends on the Eh-pH balance in the soil. In acid soils with oxidizing conditions, the iodate anion is converted to iodide, and all the unbound iodine is then available to be converted to volatile iodine. Importantly, soils overlying carbonate rocks usually have neutral or alkaline pH, and added iodide is converted to iodate with reduced volatilisation and therefore enhanced retention of iodine in the soil.

Iodine in the terrestrial biosphere

The major pathway of inorganic elements into plants is through the root system, followed by translocation to the upper aerial parts of the plant. For iodine, the translocation is minor; root uptake from the soil is therefore unimportant for the overall content of the plant. Gaseous iodine may be absorbed through leaf stomata or iodide may be precipitated on leaf or grass surfaces. Much of this is likely to be iodine that has been re-volatilised from iodide in the soil reservoir, and this is therefore inversely related to the amounts fixed in the soil as iodate and unable to re-enter the gas phase. Arable crops contain less than 0.05 ppm iodine. Grazing animals concentrate iodine by grazing large area of pasture, and they provide entry to the human food chain through dairy products. It is noteworthy that iodine is not mobile in plants and is not concentrated in seeds (Johnson *et al*, 2003). Grain crops such as wheat and oats are therefore a poor dietary source of iodine.

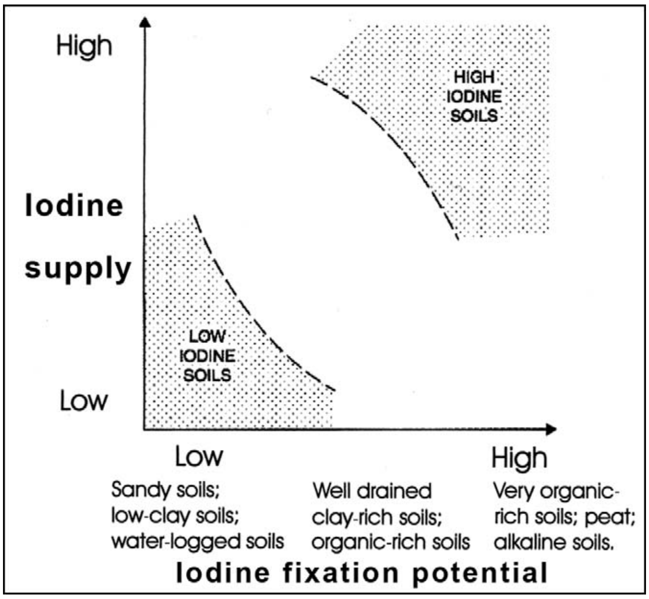


Figure 5. *Iodine and soils' fixation potential (their ability to retain iodine). Soils rich in organics, aluminum and iron oxides have high fixation potential, as do alkaline soils over carbonate rocks (after Fuge & Johnson, 1986; Fuge, 2005).*

Iodine deficiency diseases in Derbyshire

Iodine supply from soil and water

Iodine supply to the environment depends essentially on rainfall and is affected by distance from the sea and prevailing winds. Iodine content of rainfall decreases with increasing distance from the Welsh coast (Fuge, 1996). Samples of rain taken from upland areas of Wales within 12 km of the coast contained 0.005-0.006 ppm iodine, compared to 0.002 ppm from samples taken 84 km east of the coast. Similarly, the mean iodine level in the topsoils of north Derbyshire is only 5.44 ppm, compared to 14.7 ppm in soil samples from within 20 km of the Welsh coast; Derbyshire may thus be described as a relatively low-iodine environment (Fuge & Long, 1989).

Nevertheless, mean iodine levels in top soils are higher in Derbyshire, than in some non-goitrous areas of Britain (Table 1). Furthermore, the distribution of iodine in topsoils is not uniform; iodine content in topsoils overlying limestone bedrock in north Derbyshire, the area of goitre endemia, is greater than that in topsoils of adjacent non-goitrous areas where the underlying lithology is sandstone or shale. This implies that soil iodine in the limestone area is bound, and is therefore not bio-available. Soils in limestone areas are generally well drained and neutral to alkaline, and it is suggested that iodine is present predominantly as the non-volatile iodate rather than the iodide anion. Reduced re-volatilisation permits less deposition on leaves and plants for consumption by humans, either directly, or secondarily after concentration within grazing cattle. There is no need to invoke the action of vegetable goitrogens, because the Eh-pH values in limestone areas produce less mobile iodine (Johnson *et al*, 2003) and uptake by plant roots of iodate is also lower than that of iodide. There are often multiple factors that produce disease.

Dietary factors and possible goitrogens

In the 19th century, prior to the coming of the railways, the diet of poor people in rural limestone districts of Derbyshire was dependant on restricted local produce from soil in which iodine was not bio-available. Oatcakes, low in iodine, were a dietary staple (Farey, 1813) and a predeliction for them was considered responsible for goitre in Matlock (Kelly & Snedden, 1958). The dietary intake of iodine was marginal, and each person`s thyroid status, was liable to be tipped into negative balance by dietary goitrogens. There is no remaining direct evidence for dietary goitrogens in 19th century Derbyshire, but brassica vegetables (including cabbage, brussel sprouts, kale and yellow turnips) featured in the restricted diet of the rural poor; these are rich in goitrin, a thiourea-like compound that inhibits thyroid hormone synthesis. A modern parallel exists: there was a significant increase of goitre, particularly in the age group of 15-25 years in Belgium, during the German Occupation in WWII which was related to the increased consumption of cabbage and related goitrin rich vegetables during a time of overall food shortage and restricted diet (Kelly & Snedden, 1960).

Genetic factors

There may have been an increased genetic susceptibility to iodine deficiency diseases in the isolated communities of rural Derbyshire in the 19th and earlier centuries. Goitre and cretinism in Derbyshire were commonly familial, and the frequency of close intermarriage within families in an impoverished community with poor communications was emphasized (Farey, 1813; BPP, 1968; Webb, 1886). However, not all those at risk developed goitre or cretinism. Familial aggregations with the sparing of some members suggest that genetic as well as environmental factors are involved.

There is evidence for possible genetic predisposition to IDD in Derbyshire. The ability to taste the bitterness of thiourea chemicals is genetically controlled, and is linked to blood group inheritance (Mourant et al, 1978). About 30% of adult Caucasians are “taste-blind” and cannot recognize thioureas placed on their tongues; about 70% are “tasters”. Taste aversion may have an advantage, in avoidance of bitter tasting (to “tasters”) brassica vegetables containing thioureas, which eaten in large amounts are goitrogenic. Thyroid deficiency diseases are relatively uncommon among “tasters”, which may be attributed to avoidance of brassica vegetables (Tepper, 1998). A higher incidence of “taste-blind” people in Derbyshire than in the Lancaster area is correlated with the higher frequency of goitre in Derbyshire (Cartwright & Sunderland, 1967, Sunderland & Cartwright, 1968). Moreover, the frequency of “taste-blind” females is significantly higher among the descendents of patients with goitre than in the control population.

Soil type related to bedrock	**Iodine range, ppm (mean)**	**Source**
N. Derbyshire, limestone ~80-100 km from coast	2.58 - 26.0 (8.2) (6.58 ex.1*)	Fuge & Long, 1989
Derbyshire, shale, sandstone & dolomite ~80-100 km from coast	1.88 - 8.53 (3.44)	Fuge & Long, 1989
Derbyshire, limestone ~80-100 km from coast	0.56 - 4.6 (2.4)	Saikat et al, 2004
Derbyshire, all samples ~ 80-100 km from coast	1.88 - 26.0 (5.44) (4.68 ex.1*)	Fuge & Long, 1989
Great Britain, clay parent material	2.1 - 8.9 (5.2)	Whitehead, 1984
Great Britain, sandstone	1.7 - 5.4 (3.7)	Whitehead, 1984
Midlands & Welsh Borders >70 km from coast	< 5	Fuge, 1996
Coastal & Mid-Wales	10 - 25	Fuge, 1996

Table 1. *Iodine content of soils and underlying bedrock;*
** mean values excluding single outlying high value.*

Conclusion

Iodine deficiency diseases are due to an inadequate intake of dietary iodine or metabolic interference with the hormone synthesis. The dietary deficiency may reflect absolutely low levels of environmental iodine or environmental conditions which retain iodine in the soil making it non-bio-available. On limestones, a key factor is the Eh-pH soil environment that ensures that most soil iodine is bound as the iodate anion. This form of iodine is less volatile and therefore effectively non-available, as it cannot re-volatilise to be absorbed into leaves and precipitated onto grasses, where it can enter the human food chain through the critical link of grazing cattle. The limestone areas of Derbyshire have these soil conditions. However, iodine deficiencies are clearly polygenetic. In by-gone Derbyshire, the basic environmental deficiency was amplified by a restricted diet, possibly containing vegetable goitrogens and expressed in genetically predisposed members of the community. In other parts of the world the distribution of IDD is due to regionally low levels of iodine in areas of low rainfall and great distances from the oceans again with augmentation by goitrogens and genetic factors but intriguingly there now appears to be evidence that the local bedrock and the tectonic environment may be important factors.

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The Triassic System in Warwickshire

Jonathan D. Radley

Abstract. Warwickshire's Triassic strata are a mainly clastic Scythian-Rhaetian succession. The Sherwood Sandstone and Mercia Mudstone groups are assigned to the three structural settings of the Hinckley and Knowle Basins separated by the Coventry Horst. In the basinal areas the Sherwood Sandstone fines up from pebbly braidplain facies (Polesworth and Kidderminster Formations) into sandy braidplain and meanderplain facies (Bromsgrove Sandstone). The basal Hopwas Breccia crops out on the western margin of the Hinckley Basin. The Bromsgrove Sandstone onlaps the horst, with fossils that can be assigned to both terrestrial and aquatic habitats. The overlying Mercia Mudstone Group attests to a Mid-Late Triassic continental desert environment with windblown dust, periodic floods and ephemeral lakes. Within the Mercia Mudstone, the Arden Sandstone represents a fluvial interval with some marginal marine influences, and has yielded a mixed terrestrial-aquatic biota in the Knowle Basin. The relatively fossiliferous Penarth Group attests to Late Triassic (Rhaetian) marine transgression. Key Triassic sites are protected as SSSIs and RIGS.

The central English county of Warwickshire (Fig. 1) occupies part of the wide outcrop of generally gently dipping Triassic and Jurassic strata that runs from the Dorset and Devon coast in southwest England to the Yorkshire coast in the northeast. The broadly spindle-shaped Warwickshire Coalfield diversifies the regional outcrop pattern (BGS, 2001). There, the bedrock geology is dominated by an Upper Carboniferous to Lower Permian red-bed succession (Warwickshire Group), fringed in the north by Coal Measures, Millstone Grit, and older igneous and sedimentary rocks of Palaeozoic and Neoproterozoic age, as in the Nuneaton Inlier (Shotton, 1960; Hains & Horton, 1969; IGS, 1983; Bridge *et al*, 1998; Fig. 1).

This paper focuses on Warwickshire's Triassic successions, dominated by the Sherwood Sandstone and Mercia Mudstone groups (Warrington *et al*, 1980; Fig. 2). The Sherwood Sandstone Group rests unconformably on rocks ranging from Precambrian (Neoproterozoic) up to early Permian in age (Warrington *et al*, 1980; Bridge *et al*, 1998), reflecting post-Variscan uplift and erosion. The Sherwood Sandstone and Mercia Mudstone are developed largely as non-marine sediments deposited in hot, semi-arid to arid continental settings, approximately 15-20º north of the equator, within the northern part of the Permian-Triassic Pangaea supercontinent (Ruffell & Shelton, 2000; Benton *et al*, 2002). Fossils are very rare in these rocks and standard Triassic stage boundaries cannot be accurately located. Present evidence suggests that the strata range through much of the Triassic System (Scythian Series up to Rhaetian Stage; Warrington *et al*, 1980; Fig. 2), though in places the basal Hopwas Breccia and lower part of the Sherwood Sandstone is possibly of Permian age (Worssam & Old, 1988). Above the Mercia Mudstone, the relatively fossiliferous latest Triassic (Rhaetian) Penarth Group is largely marine in origin. The Triassic-Jurassic (Rhaetian-Hettangian) boundary is defined in Britain by the first occurrence of the ammonite genus *Psiloceras* (Cope *et al*, 1980; Warrington *et al*, 1980). This occurs within the Wilmcote Limestone Member (basal Lias Group) in the Avon Valley region of southwestern Warwickshire (Old *et al*, 1991; Ambrose,

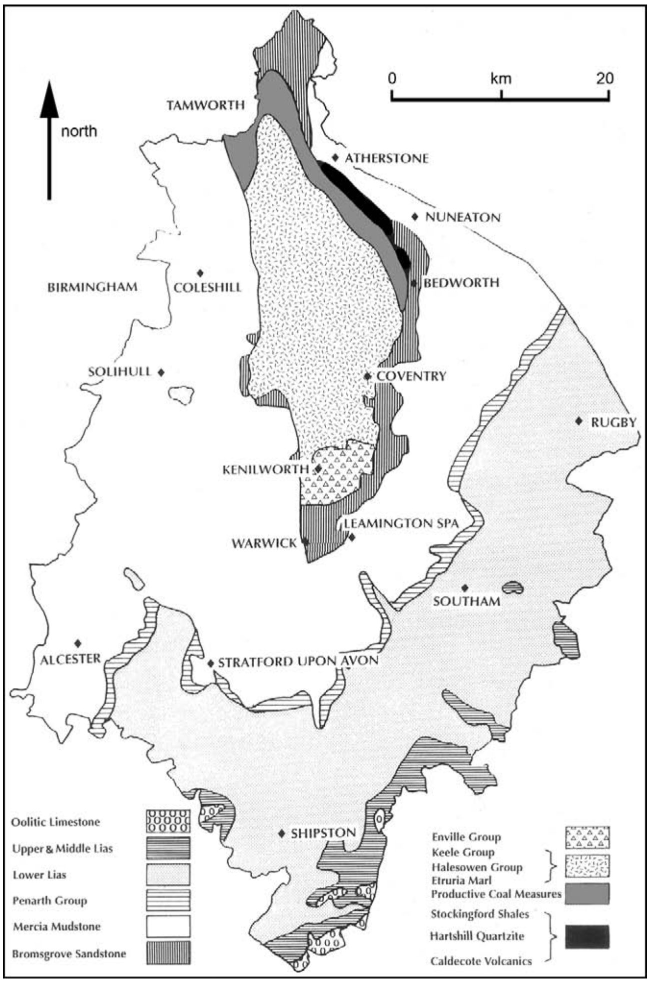

Figure 1. *Outline solid geological map of Warwickshire, together with the Borough of Solihull and the City of Coventry (from Tasker, 1990, with permission).*

2001) and in the Saltford Shale Member near Rugby (Old *et al*, 1987).

Overall, the Triassic strata demonstrate the shallow regional structural dip towards the southeast and crop out extensively around the coalfield. In the Avon Valley and Warwick-Rugby areas, the Mercia Mudstone outcrop is flanked down-dip by that of the overlying Penarth Group and Lias Group (Lower Jurassic) strata (Hains & Horton, 1969; IGS, 1983; BGS, 2001). An outlier of Penarth Group strata occurs at Copt Heath, Knowle (Brodie, 1865; Eastwood *et al*, 1925), 17 km north of the main outcrop.

Triassic strata were well exposed in sandstone quarries and clay pits during the nineteenth and early to mid twentieth centuries. Many of these sections are no longer extant. However small natural sections are common, albeit often deeply weathered. Accessible exposures also occur in canal cuttings, shallow road cuttings and sunken lanes. The Scythian-?Ladinian Bromsgrove Sandstone Formation (Sherwood Sandstone Group) and the Carnian Arden Sandstone Formation (Mercia Mudstone Group) formerly yielded building stone, seen in many towns and villages around the southern end of the coalfield (Matley, 1912; Old *et al*, 1987). Thinner sandstones within the Mercia Mudstone Group, termed ‘skerries’ (see below), have probably also been quarried. Rhaetian Langport Member (‘White Lias’) limestones have been quarried on a small scale for building stone, cement and agricultural lime along a narrow outcrop from the Stour Valley to Rugby (Richardson, 1912; Swift, 1995). It is still intermittently worked near Loxley, southeast of Stratford-upon-Avon. The Wilmcote Limestone of the Avon Valley has supplied flooring, paving and walling stone, as well as raw material for cement manufacture (Brodie, 1868). The red-brown mudstones of the Mercia Mudstone Group have been quarried for brick clay, as at Leamington, Knowle and Stonebridge, and were also used for ‘marling’ light land (Twamley, 1878; Old *et al*, 1991; Powell *et al*, 2000). Additionally they were mined for gypsum at Spernall, north of Alcester (Old *et al*, 1991). The Early Triassic Polesworth Formation has been dug for sand and gravel in north Warwickshire (Worssam & Old, 1988).

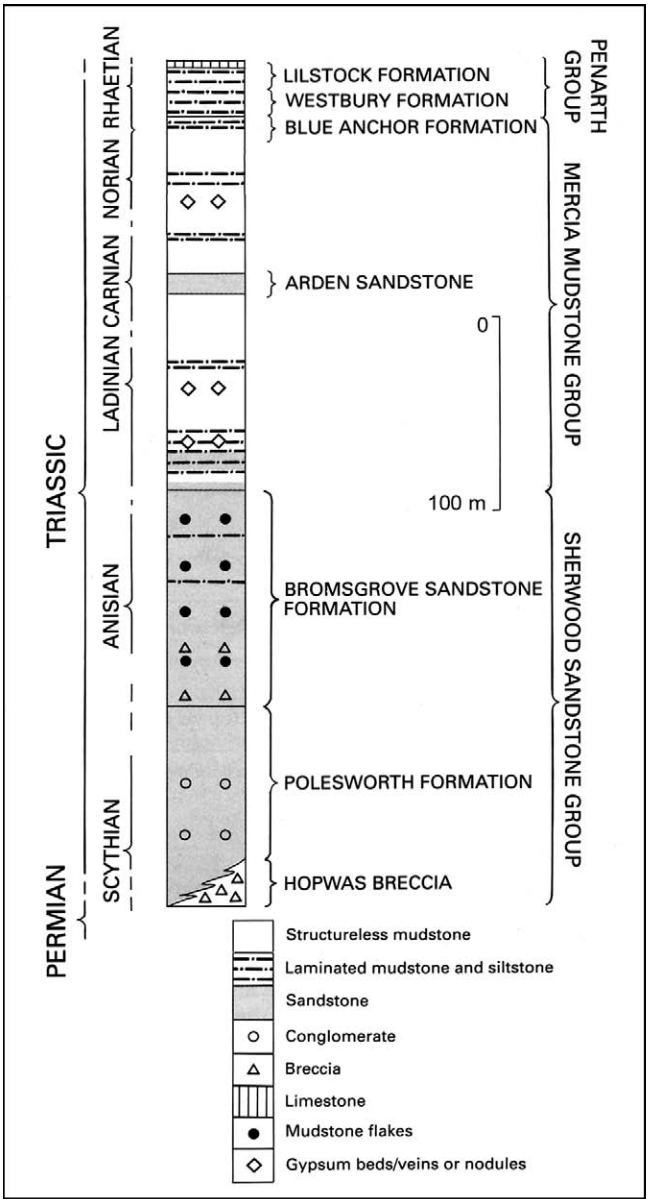

Figure 2. *Generalised vertical section of Triassic strata in Warwickshire (from Bridge et al, 1998, with permission).*

The Triassic strata of Warwickshire have a long research history, stemming from the early nineteenth century when exposures were more prevalent than they are today (see above). Historically, the succession has been associated with such eminent researchers as Roderick Murchison (1792-1871), Hugh Strickland (1811-1853), Peter Brodie (1815-1897), Linsdall Richardson (1881-1967), Leonard Wills (1884-1979) and Fred Shotton (1906-1990). Only a few of the more important older references are cited herein. Modern knowledge of the Warwickshire Triassic is due largely to investigation and interpretation of surface exposures and borehole sections by the British Geological Survey. Survey memoirs and Geological Conservation Review volumes cited herein should be consulted for more comprehensive details of earlier works.

Selected geological sites in the United Kingdom are afforded statutory and non-statutory protection as Sites of Special Scientific Interest (SSSIs) and Regionally Important Geological Sites (RIGS) respectively (Harley, 1994; Ellis *et al*, 1996). Warwickshire currently (2005) boasts three SSSIs and thirteen RIGS selected partly or wholly for their Triassic interest. Additionally, the Warwickshire Museum has recently produced a series of local geodiversity action plans (LGAPs) that will facilitate planned conservation and management of several Permian-Triassic fossil sites (Radley, 2004). This paper summarises Warwickshire’s Triassic geology with reference to protected sites. For the purposes of this account the county is taken as the area defined by the 1974 local government reorganisation, and additionally, the Borough of Solihull and City of Coventry (Fig. 1).

Structural framework

Late Permian times in central England were marked by east-west crustal extension and continental rifting, attributed to tensional stresses linked to the opening of the North Atlantic Ocean (Ruffell & Shelton, 2000). This resulted in reactivation of favourably oriented faults in the Midlands Microcraton basement, predominantly those with north-south (Malvernoid) trends (Audley-Charles, 1970; Chadwick, 1985; BGS, 1996). Further reactivation probably occurred intermittently throughout much of the Triassic (Holloway, 1985b, c; Ruffell & Shelton, 1999), and the strata were deposited principally as syn-rift successions in the resultant range of graben and half-graben; some representing inverted Variscan 'highs' (Chadwick, 1985; Holloway, 1985a; Chadwick & Smith, 1988; Ruffell & Shelton, 2000).

Warwickshire's Triassic rocks largely occupy three structural units (Warrington *et al*, 1980; Bridge *et al*, 1998; Benton *et al*, 2002; Fig. 3), reflecting Late Permian to Early Triassic reactivation of major Malvernoid and NW-SE trending (Charnoid) faults (Audley-Charles, 1970), and Warwickshire's location near the apex of the concealed Midlands Microcraton (Lee, Pharaoh & Soper, 1990; BGS, 1996). Firstly, northeastern Warwickshire (Mease lowlands and parts of the High Cross plateau; Warwickshire County Council, 1993) marks the southwestern part of the Hinckley Basin (Figs 3, 4), generated through Late Permian structural inversion along the Charnoid Polesworth Fault of an area of relative Variscan uplift (Worssam & Old, 1988; Bridge *et al*, 1998). Parts of the Sherwood Sandstone Group thicken towards the Polesworth Fault, suggesting that the Hinckley Basin is a half-graben (Worssam & Old, 1988).

Secondly, west of the Polesworth Fault, the Warwickshire Coalfield and its concealed southern extension (Fig. 3) are characterised by a thin, relatively incomplete Triassic succession (Edmonds, Poole & Williams, 1965; Old *et al*, 1987). This area is accordingly modelled as a partly inverted Triassic 'high' (Warrington & Ivimey-Cook, 1992), termed the Coventry Horst (Old *et al*, 1987; Bridge *et al*, 1998). Thirdly, along the western edge of the coalfield, the Malvernoid Western Boundary (Meriden) and Warwick Faults mark the eastern margin of the Knowle Basin (Old *et al*, 1991; Powell *et al*, 2000; Fig. 3). The eastern part of the Knowle Basin fill occurs within western Warwickshire's Arden district between Alcester and Middleton. The Triassic succession there is thicker than that of the Hinckley depocentre, and similarly marks the site of an inverted Variscan 'high' (Holloway, 1985a).

Depocentre boundaries are poorly defined south and east of the coalfield. The subcropping Triassic strata thin overall to the south and east of Warwickshire, towards the London Platform (Hains & Horton, 1969; Warrington *et al*, 1980). West of Stratford-upon-Avon, the Malvernoid Inkberrow-Weethley Fault system marks part of the eastern margin of the major Permian-Triassic Worcester Basin (Old *et al*, 1991; Ambrose, *pers. comm.*), of which the Knowle Basin is a subsidiary (Chadwick & Smith, 1988). East of Kenilworth and Leamington, the Charnoid Princethorpe Fault (Fig. 4) might relate to the margin of the Hinckley Basin (Old *et al*, 1987).

Stratigraphy and palaeoenvironments

Southern British Triassic successions are characterised by three major lithostratigraphic divisions (Warrington *et al*, 1980). The lower, Sherwood Sandstone Group is a largely alluvial succession deposited under a hot, seasonal climatic regime with both humid and arid characteristics (Ruffell & Shelton, 1999). The overlying Mercia Mudstone Group provides evidence for a dominantly arid Late Triassic climate (see below) and a somewhat featureless, exposed landscape, bordered by extensively peneplaned massifs

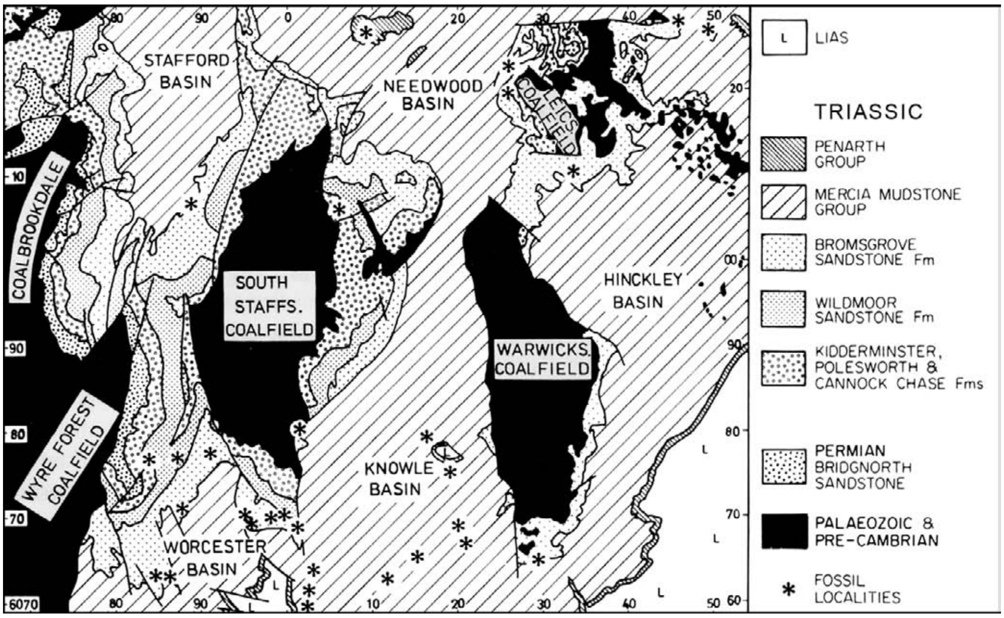

Figure 3. *Distribution of Triassic strata in the English Midlands (from Warrington et al, 1980, with permission).*

(Anderton *et al*, 1979; Audley-Charles, 1970; Warrington & Ivimey-Cook, 1992). Widespread reddening of the mudstones is due to early diagenetic oxidation, reflecting the prevailing aridity (Benton *et al*, 2002). Above, the Penarth Group includes fossiliferous mudstones and micritic limestones of transgressive marine origin (Richardson, 1912; Benton *et al*, 2002).

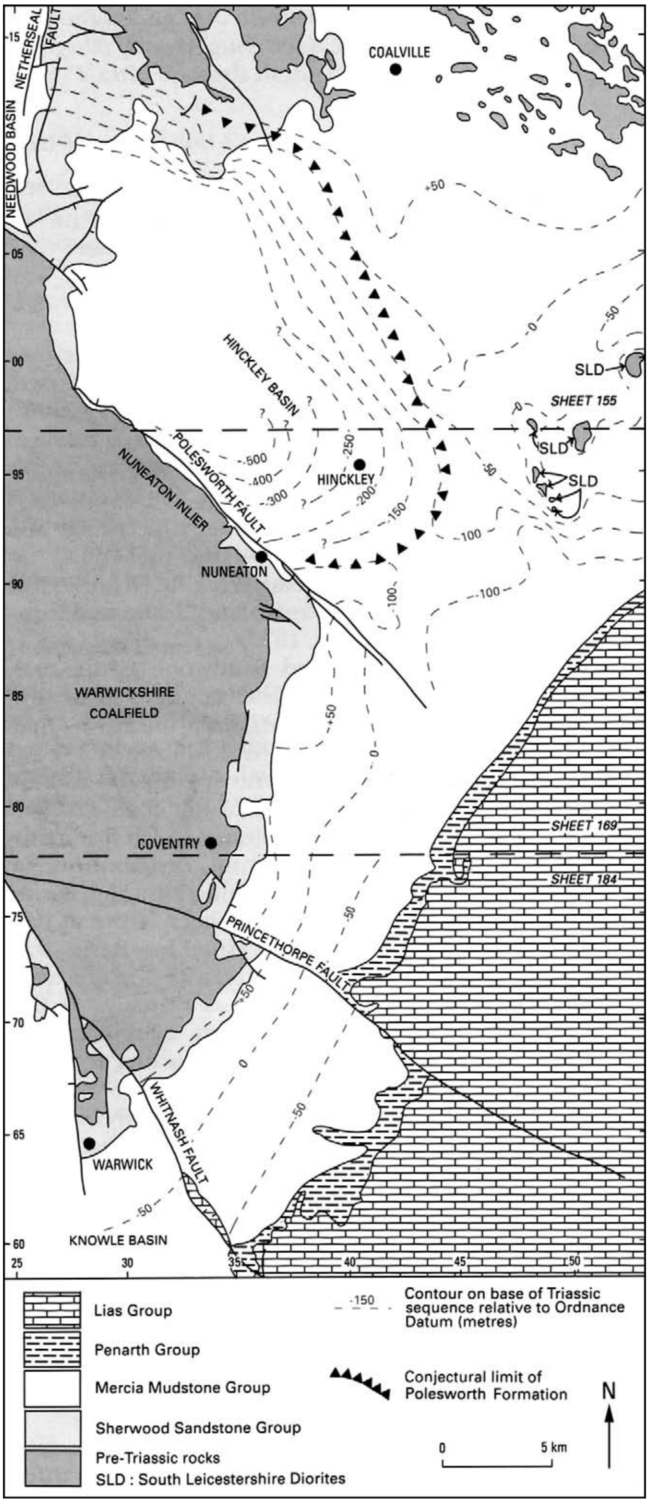

Figure 4. *Sketch map of the geological setting of the Hinckley Basin (from Bridge et al, 1998, with permission).*

Sherwood Sandstone Group

The Hopwas Breccia and overlying Polesworth Formation (Sherwood Sandstone Group) represent the oldest part of the Hinckley Basin fill in northeastern Warwickshire (Figs 2, 3, 4). The Hopwas Breccia is provisionally assigned an Early Triassic (Scythian) age, though it could equally be partly or wholly Late Permian in the absence of diagnostic fossils (Warrington *et al*, 1980; Worssam & Old, 1988). It thickens westwards towards the Polesworth Fault (up to around 12 m) and forms a narrow outcrop northeast of Polesworth. Several metres of red-brown sandy breccia are still exposed in the Stiper's Hill road cutting (SK271027; part of the Stiper's Hill RIGS). The coarse fraction comprises fragments of Cambrian sandstone and rarer Carboniferous limestone, as well as igneous and slatey metasedimentary lithologies (Brown, 1889). The breccia is currently interpreted as scree eroded mainly from the nearby horst margin, reworked by flash floods, and deposited in proximal fan settings on the adjacent basin floor (Warrington *et al*, 1980; Bridge *et al*, 1998).

The overlying Scythian Polesworth Formation comprises up to around 200 metres of poorly cemented sandstones, conglomerates and red-brown mudstones, outcropping close to the Leicestershire border between the Polesworth and Warton faults. A disused pit (now a RIGS) northeast of The Round Berry (SK277038), exposes about 7 m of buff sandstone and conglomerate (Fig. 5). The clast suites are dominated by well-rounded pale quartzites, with sparser vein-quartz and cherts. The conglomerates typify the widespread pebbly braidplain facies of the Sherwood Sandstone Group in southern Britain (Warrington, 1970; Steel & Thompson, 1983; Smith, 1990; Benton *et al*, 2002). Wills (1948, 1956, 1970) attributed the Polesworth Formation to a 'Polesworth River', draining from the 'Mercian Uplands' (London-Ardennes Landmass of Warrington & Ivimey-Cook, 1992) to the southeast of the Warwickshire Coalfield. However, the abundant quartzite clasts match those of the approximately contemporaneous Kidderminster Formation of the Worcester Basin (West Midlands; Fig. 3), suggesting fluvial sediment exchange across the horst (Worssam & Old, 1988; Warrington & Ivimey-Cook, 1992). It is generally agreed that the quartzites were sourced predominantly from the region of the Armorican massif (Brittany-Cornwall) by a large-scale, seasonally charged, axial river system ('Budleighensis River' of Wills, 1956, 1970) draining northwards and northeastwards through the subsiding graben system of the Worcester Basin, and its associated depocentres (Audley-Charles, 1970; Wills, 1970; Holloway *et al*, 1989; Warrington & Ivimey-Cook, 1992).

The considerable thickness of sediment involved indicates rapid subsidence on the hanging wall of the Polesworth Fault during Scythian times. Comparable Early Triassic conglomerates (assigned to the Kidderminster Formation) have been encountered in

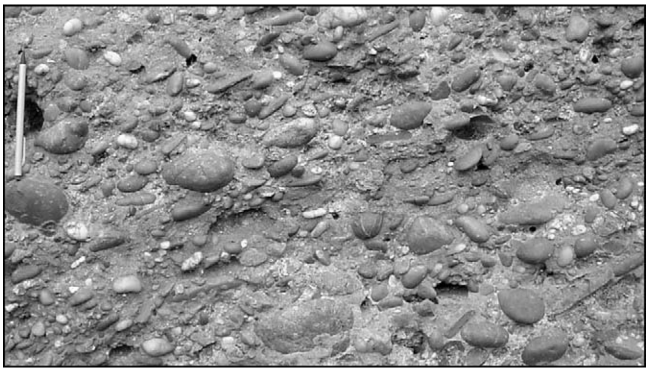

Figure 5. *Polesworth Formation pebble beds exposed in disused quarry northeast of The Round Berry, near Warton (SK277038). Beds are dominated by pebbles of quartzite and vein-quartz, and dip southeast. Pencil is 150 mm long.*

the subsurface of the Knowle Basin (e.g. Blyth Bridge Borehole; SP212898; Powell *et al*, 2000) and may locally persist as far eastwards as the Coventry Horst (Warrington, 1970; Old *et al*, 1991). The present-day distribution of the Polesworth and Kidderminster formations in Warwickshire (Fig. 1) mimics that defined by synsedimentary faulting in Triassic times (Warrington & Ivimey-Cook, 1992).

The Hinckley Basin had filled sufficiently by late Sherwood Sandstone times to allow alluvial deposition on the eastern margin of the Coventry Horst. Thus, the Scythian-?Ladinian Bromsgrove Sandstone Formation overlies and oversteps the Polesworth Formation. It rests unconformably on a palaeoslope of steeply dipping Cambrian sandstones at Midland Quarry RIGS, Hartshill (SP350925), near the eastern margin of the horst in the Nuneaton Inlier. There, a basal breccia comprises locally derived fragments of Cambrian sandstone and Ordovician intrusive igneous rocks and is overlain by up to 6 m of cross-bedded pebbly sandstone. Further south, boreholes and scattered exposures between Nuneaton and Coventry have revealed up to around 30 m of Bromsgrove Sandstone (Eastwood *et al*, 1923; Bridge *et al*, 1998). Fining-upward cycles have been recognised, several metres thick, each ranging from erosively-based, pebbly, feldspathic, calcite-cemented sandstones up into mudstones. Some of the latter enclose small calcareous nodules, possibly of pedogenic origin. Overall grain-size of the cycles decreases upward through the succession (Bridge *et al*, 1998).

On the southern end of the horst (Warwick district), the Bromsgrove Sandstone is up to about 30 m thick and rests unconformably on slightly folded Permian red-beds of the Warwickshire Group. It is similarly characterised by fining-upward cycles of pale, fine to medium-grained, calcite or feldspar-cemented, feldspathic and/or micaceous sandstones (some pebbly), and red-brown mudstones (Shotton, 1929; Wills, 1976; Old *et al*, 1987). Within the sandstones, cross-bedding on a variety of scales indicates flow from the south and west (Old *et al*, 1987; Warrington & Ivimey-Cook, 1992), and soft-sediment deformation is widespread. The Bromsgrove Sandstone thickens rapidly westwards across the Warwick Fault into the Knowle Basin. Thicknesses of nearly 50 m were seen in the Heath End and Shrewley boreholes (SP232609, SP222676); probably more than 70 m at Rowington (SP209688) and 182 m in the Blyth Bridge Borehole near Coleshill (Old *et al*, 1991; Powell *et al*, 2000). Further south, the highest part of the formation yielded a sparse assemblage of spores and organic-walled microplankton in the Knights Lane borehole (SP224550), Stratford-upon-Avon (Warrington, 1974). Boreholes in the Stratford area prove the presence of Upper Carboniferous and/or Permian red-beds (Warwickshire Group) beneath the Bromsgrove Sandstone (Richardson & Fleet, 1926; Williams & Whittaker, 1974; Chadwick & Smith, 1988). There, the basal breccias include probable ventifacts, suggestive of a deflation surface (e.g. Welcombe Fields Borehole, SP212562; Williams & Whittaker, 1974; Wills, 1976). The Bromsgrove Sandstone is the main source of the spa waters at Royal Leamington Spa (Richardson, 1928; Old *et al*, 1987).

West of the county boundary, beyond the Birmingham Fault, the late Scythian Wildmoor Sandstone intervenes between the Kidderminster and Bromsgrove Sandstone formations (Wills, 1976; Powell *et al*, 2000). However, borehole sections east of the Birmingham Fault in western Warwickshire confirm that the Wildmoor Sandstone is largely or wholly absent in the eastern Knowle Basin, beneath a significant non-sequence at the base of the Bromsgrove Sandstone. This might equate to the Hardegsen Disconformity, recognised in NW Europe as due to late Scythian earth movements (Warrington, 1970; Warrington & Ivimey-Cook, 1992).

The Bromsgrove Sandstone marks general maturation of the central English river systems by Anisian-Ladinian times. Widely recorded fining-upward cycles suggest ephemeral fluvial settings, and periodically rapid deposition from waning currents (Holloway, 1985b). Thicker sand bodies are interpreted as channel deposits, floored by conglomeratic lags. Intercalated thinly-bedded sandstones and mudstones are interpreted as overbank alluvium. The overall fining-upward Bromsgrove succession, well documented from the Coventry Horst (see above), suggests a general shift from low-sinuosity braidplain to meanderplain settings through time (Warrington, 1970; Warrington *et al*, 1980; Warrington & Ivimey-Cook, 1992). The record of microplankton near the top of the formation in the Knights Lane Borehole suggests a weak marine influence (Warrington, 1974), possibly equating to a marine transgression into the English Midlands from the North Sea area during the Middle Triassic (Audley-Charles, 1992; Benton *et al*, 2002). A similar record has been obtained from broadly contemporaneous strata (Sugarbrook Member) at Bromsgrove (Worcester Basin), west of Warwickshire.

During the nineteenth century, several quarries in the Bromsgrove Sandstone of the Warwick and Leamington area yielded a vertebrate fauna. Amongst these, Coten End Quarry SSSI (SP290655) was the source of numerous disarticulated remains of fishes, fish-eating amphibians, and terrestrial reptiles including herbivorous *Rhynchosaurus brodiei* Benton (Figure 6) and carnivorous *Bromsgroveia walkeri* Galton (Benton & Spencer, 1995 and references therein). Many or all of the fossils were from the 'Dirt-bed' (Murchison & Strickland, 1840); a poorly cemented unit in the lower part of the exposed succession (Old *et al*, 1987). Guy's Cliffe SSSI (SP293668; a quarried river cliff on the River Avon) yielded a lower jaw of the fish-eating amphibian *Mastodonsaurus* (Benton & Spencer, 1995 and references therein).

Mercia Mudstone Group

The Bromsgrove Sandstone fines up into the Mercia Mudstone Group through a series of thin-bedded sandstones, siltstones and red-brown mudstones, broadly of late Anisian-early Ladinian age, that reach around 12 m thick near Nuneaton (Bridge *et al*, 1998). This transitional unit, formerly known as the Waterstones (Hull, 1869) and Passage Beds (Richardson, 1928) is now correlated with the Tarporley Siltstone Formation of the Cheshire Basin (Ambrose, *pers. comm.*). The transition beds overstep the Hinckley Basin margin onto Precambrian (Charnian) volcanic rocks at Judkins' Quarry RIGS, Hartshill (SP348930). Though poorly exposed, the Mercia Mudstone crops out widely round the coalfield, forming the northeast Warwickshire lowlands, much of the Arden district, and underlying substantial parts of the Avon Valley and the Warwick-Princethorpe area (Shotton, 1960; IGS, 1983). Scattered outcrops occur on the Coventry Horst, as in the Binley and Walsgrave area (BGS, 1994).

Figure 6. *Type specimen of the skull of* Rhynchosaurus brodiei *Benton (Warwickshire Museum specimen G6097) and right dentary (G950); both from the Bromsgrove Sandstone Formation of Coten End Quarry, Warwick (SP290655). Scale is graduated in millimetres.*

The Mercia Mudstone is up to around 400 m thick in the Knowle Basin (Powell *et al*, 2000) and dominated by unfossiliferous, red-brown, largely structureless blocky mudstones and siltstones comprising clay minerals (Jeans, 1978), iron oxides, carbonates and quartz grains (some wind-polished). The mudstones include chemically reduced green spots and beds, thin siltstones, and lenticular, fine-grained, greenish-grey, calcite and/or dolomite-cemented sandstone beds informally termed 'skerries' (Jeans,1978; Old *et al*, 1987, 1991; Bridge *et al*, 1998; Powell *et al*, 2000). Small, radioactive nodules were noted in the Knowle Borehole (SP188778; Harrison *et al*, 1983). Veins and nodules of gypsum have been encountered in numerous boreholes (Richardson, 1928; Williams & Whittaker, 1974; Old *et al*, 1987, 1991; Bridge *et al*, 1998). Thick halite deposits, present in the Worcester Basin, are absent in Warwickshire. The Home Farm Borehole (SP432731), near Stretton-on-Dunsmore, also revealed dolomitic nodules and mud-flake breccias (Old *et al*, 1987). More rarely the mudstones are laminated, slickensided, suncracked, or reveal soft-sediment deformation (Old *et al*, 1987). Fining-upward cycles have been identified, typically comprising fine-grained sandstones passing up through dolomitic mudstones into less dolomitic mudstones (Old *et al*, 1991; Powell *et al*, 2000). Other cycles noted by Old *et al.* (1991) showed alternations of laminated and blocky mudstone similar to those described by Arthurton (1980). A section was formerly well exposed at Jackson's Brick Pit RIGS, Stonebridge (SP205826; Fig. 7). There, the higher part of a roughly 30 m succession of red-brown blocky mudstones featured thin, fine-grained, cross-bedded sandstones (Powell *et al*, 2000).

The Mercia Mudstone facies is extensive throughout both onshore and offshore Britain's Triassic basins, but its depositional environments remain poorly resolved. The upward transition from the Sherwood Sandstone into the Mercia Mudstone reflects breakdown of major river systems. This has been attributed to marine transgression (Warrington, 1970), geomorphic decay of source massifs (Warrington & Ivimey-Cook, 1992), as well as to increasing aridity, with or without rifting-induced fragmentation of drainage patterns (Ruffell & Shelton, 1999, 2002). The widespread oxidation of the mudstones confirms their deposition under an arid climatic regime (Benton *et al*, 2002). Some workers (e.g. Tucker, 1977; Milroy & Wright, 2000) have invoked an essentially lacustrine environment involving periodic emergence. Others have envisaged a mainly emergent setting, characterised by accretion of wind-blown dust on a damp surface with a high water table, as well as in shallow lakes (Arthurton, 1980; Barclay *et al*, 1997; Jefferson *et al*, 2002). Geochemical and sparse palaeontological evidence confirms a marine influence on deposition (Arthurton, 1980; Leslie *et al*, 1993; Ruffell & Shelton, 1999), implying periodic seawater incursions.

The models of Arthurton (1980) and Jefferson *et al* (2002) seem broadly applicable to the Warwickshire Mercia Mudstone, involving aeolian deposition of the massive mudstones on emergent flats, and of the laminated units in shallow water-bodies. Gypsum formed contemporaneously, close to the sediment surface, deposited from interstitial brines linked to the high, saline water table, or possibly in hypersaline lakes (Warrington & Ivimey-Cook, 1992). Thin siltstones and sandstones (‘skerries’) formed by rapid runoff from flash floods, giving rise to ephemeral braided streams (Powell *et al*, 2000). Arthurton (1980) compared the inferred Mercia Mudstone palaeoenvironments to those of the Rann of Kutch, arid coastal flats on the Indian-Pakistan border, periodically inundated by seawater as well as continental runoff (also see Glennie & Evans, 1976)

In the upper part of the Mercia Mudstone, the Arden Sandstone Formation typically comprises interbedded, grey-green, laminated, cross-bedded, bioturbated and massive sandstones, siltstones and red to grey-green mudstones. Palaeocurrent measurements from cross-bedding indicates easterly flow (Old *et al*, 1991). The formation outcrops extensively in southwestern Warwickshire (Knowle Basin), where it reaches a maximum thickness of around 11 m (Old *et al*, 1991). It is also well known from the Warwick-Princethorpe area (BGS, 1984). Exposures in the Shrewley and Rowington areas, west of Warwick, have yielded an important suite of body- and trace fossils. Good sections still occur within canal cuttings at both localities (Shrewley SSSI; SP212674; Rowington RIGS; SP200692), figured by Old *et al*. (1991). The biota discovered at Shrewley includes land plants (conifers), badly preserved bivalve shells of marine aspect, conchostracans (‘clam-shrimps’), remains of sharks, bony fishes and amphibians (Old *et al*, 1991; Benton *et al*, 2002 and references therein). Reptile trackways were also encountered (Sarjeant, 1974; Tresise & Sarjeant, 1997; Fig. 8). Simple burrows occur within fine-grained sandstones at the nearby Rowington cutting. Palynomorph assemblages from the Arden Sandstone at Rowington confirm a late Carnian age (Old *et al*, 1991).

The Arden Sandstone signifies important environmental change. The presence of a terrestrial-aquatic biota with probably marine or quasi-marine elements (notably the molluscs and hybodont sharks) suggests a marginal marine environment at times, and possibly an attendant increase in humidity and/or rainfall (Benton *et al*, 2002). Sandstones and mudstones are interpreted as distributary channel and interdistributary bay deposits respectively, in an estuarine or deltaic setting (Old *et al*, 1991; Barclay *et al*, 1997). Reptile trackways attest to local subaerial exposure. The increased drainage has been tentatively attributed to Carnian isostatic lowering of parts of southern Britain, following cessation of rifting (Warrington & Ivimey-Cook, 1992). The marine influence recorded by the Arden Sandstone and its correlatives (Warrington & Ivimey-Cook, 1992) could therefore reflect enhanced connection with Tethyan sources. By early Norian times, much or all of Warwickshire had reverted to the continental environment with flash-floods, playa lakes and possible periodic marine incursions, in which the upper Mercia Mudstone accumulated (Warrington & Ivimey-Cook, 1992; Ruffell & Shelton, 1999).

The Blue Anchor Formation (Warrington *et al*, 1980; Fig. 2) at the top of the Mercia Mudstone Group comprises grey-green mudstones and siltstones, reaching around 7 m thick at Marlcliff RIGS (SP092505), a slumped and overgrown river cliff on the River Avon southwest of Stratford (Richardson, 1912). Scattered dinocysts (as in the Knowle Borehole) indicate an increasing marine influence prior to the mid-late Rhaetian (Penarth Group) transgression (Warrington & Ivimey Cook, 1992).

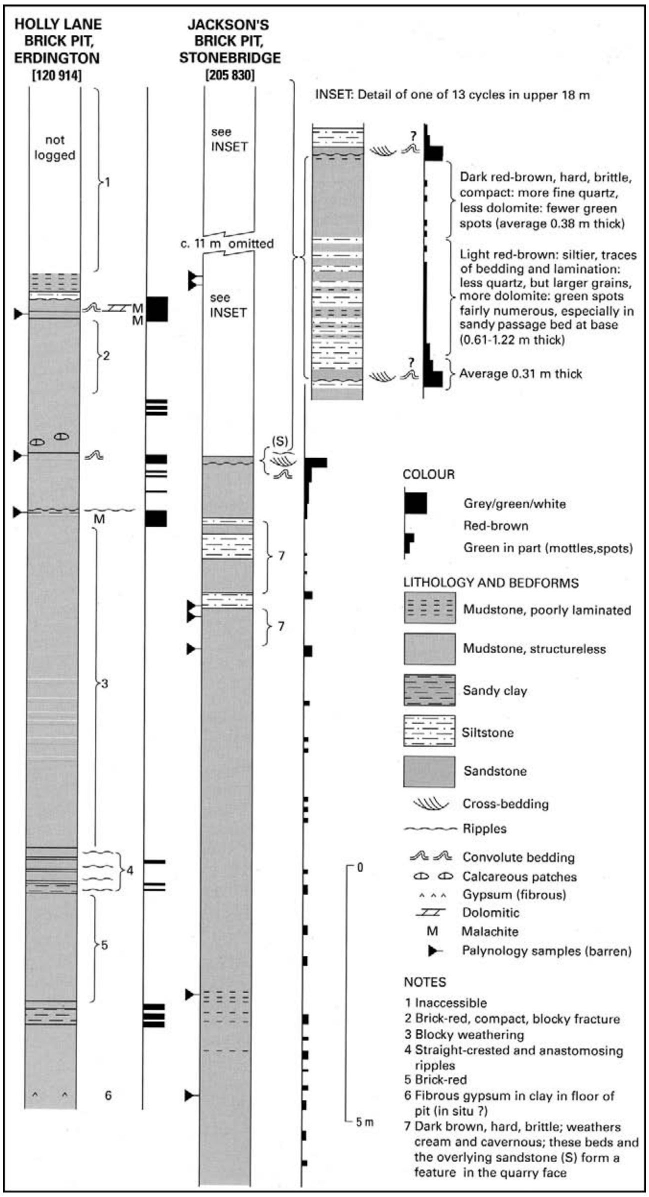

Figure 7. *Graphic log of part of the Mercia Mudstone Group at Jackson’s Brick Pit, Stonebridge (SP205830) (from Powell et al, 2000, with permission).*

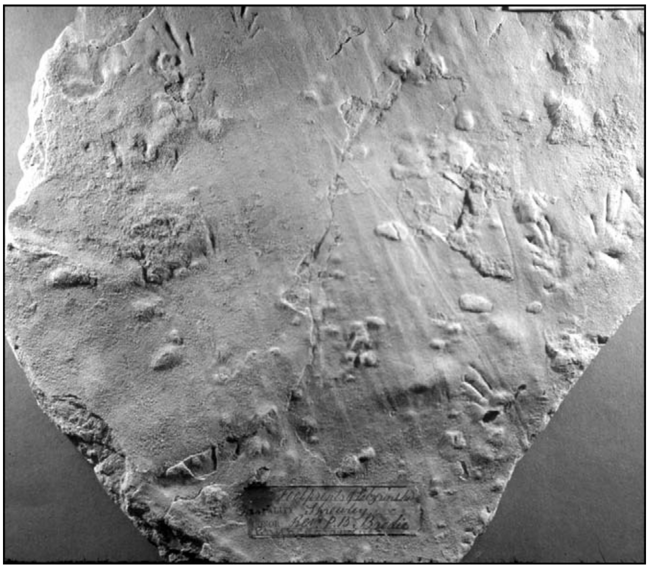

Figure 8. *Reptile tracks* (Rhynchosauroides) *preserved in thin-bedded fine-grained sandstone (Warwickshire Museum specimen G9437). Arden Sandstone Formation, Shrewley. Image is 240 mm across.*

Penarth Group

The Penarth Group (Fig. 2) marks an abrupt change in sedimentary style, replacing the continental Mercia Mudstone with fossiliferous mudstones, siltstones and limestones of quasi-marine to fully marine origin. Overlying the eroded top of the Blue Anchor Formation, the widespread but poorly exposed Westbury Formation comprises up to 8.5 m of dark-coloured, pyritic, laminated mudstone enclosing siltstone and sandstone lenticles. A synsedimentary slump structure, possibly attributable to seismic shock (Simms, 2003; Hallam & Wignall, 2004), was noted at the top of the formation in the Home Farm Borehole (Old *et al*, 1987). The mudstones yield a macrofauna dominated by epibenthic and shallow-burrowing marine bivalves, and fish debris (Richardson, 1912; Williams & Whittaker, 1974; Old *et al*, 1987). Palynological samples from Westbury mudstones in the Stockton Locks Borehole (SP430649) revealed abundant miospores, organic-walled microplankton and foraminiferal test linings (Old *et al*, 1987).

Black fissile mudstones of the Westbury Formation were formerly exposed above the Blue Anchor Formation at Marlcliff (Richardson, 1912; and above). Further northeast, the Westbury Formation is absent at Round Hill road cutting RIGS (SP143618) near Wootton Wawen, where the overlying Cotham Member (see below) rests directly on the Blue Anchor Formation. This is probably due to the proximity of the Malvernoid Vale of Moreton Axis that evidently functioned as a structural 'hinge' on the eastern margin of the Worcester Basin in the Late Triassic to Early Jurassic (Old *et al*, 1991). Following general marine transgression through northwest Europe (Warrington & Ivimey-Cook, 1992), the Westbury Formation confirms establishment of shallow marine environments over much of central England. The laminated, organic-rich nature of the sediments suggests that bottom waters were generally poorly oxygenated (Swift, 1999 and references therein), but periodically colonised by a bivalve-dominated fauna.

The Westbury Formation is overlain by the Cotham Member; the lowest unit of the Lilstock Formation (Fig. 2). The Cotham Member reaches 12 m thick at Rugby (Old *et al*, 1987). The dominant lithologies are buff- to grey-green calcareous mudstones enclosing lenticular siltstones, yielding sparse macrofaunas that include conchostracans, and bivalves of marine aspect. These, and the presence of dinocysts and foraminifera (e.g. Knowle and Stockton Locks boreholes; Old *et al*, 1987, 1991), suggest marine-influenced, lacustrine or lagoonal environments (Warrington & Ivimey-Cook, 1992). Calcareous mudstones at the top of the member are exposed at the Ufton Landfill Site RIGS (SP393617) and at Southam Cement Works RIGS, Long Itchington (SP420630), east of Leamington.

In the Avon Valley of southwest Warwickshire, the highest subdivision of the Lilstock Formation, the Langport Member (see below), is absent. There, the Cotham Member is normally overlain by the alternating grey-coloured, argillaceous limestones (some nodular and/or shelly) and calcareous mudstones of the Late Triassic and Early Jurassic Wilmcote Limestone Member (Blue Lias Formation). These strata reach about 8 m thick at Temple Grafton (Ambrose, 2001) and are still exposed at the Wilmcote Quarry SSSI (SP151594) and Temple Grafton quarry RIGS (SP121539). There, they formerly yielded many marine fossils including ammonites, crustaceans, fishes and reptile remains (Brodie, 1868; Simms *et al*, 2004). The basal Jurassic ammonite *Psiloceras planorbis* has been collected from the lower part of the member (Old *et al*, 1991).

The Wilmcote Limestone disappears to the southeast across the Vale of Moreton Axis, towards the London Platform (Ambrose, 2001). East of the Stour Valley, the Cotham Member is overlain by the Langport Member, the highest division of the Penarth Group (Swift, 1995). This is developed as grey to cream coloured, dominantly micritic and frequently bioturbated limestones with thin mudstone seams, reaching over 4 m thick at Rugby (Richardson, 1928; Old *et al*, 1987). Low-diversity macrofaunas, including solitary corals, echinoid debris, bivalves and gastropods, augment the lithological evidence for a shallow-water, restricted marine environment (Warrington & Ivimey-Cook, 1992; Swift, 1995). The member is exposed at the Southam Cement Works Quarry RIGS. Conglomeratic limestone (Fig. 9) in its upper part indicates early cementation of carbonate substrate and its subsequent disruption by storm activity (Hallam & Wignall, 2004), or possibly seismic shock (Swift, 1995; Radley & Swift, 2002).

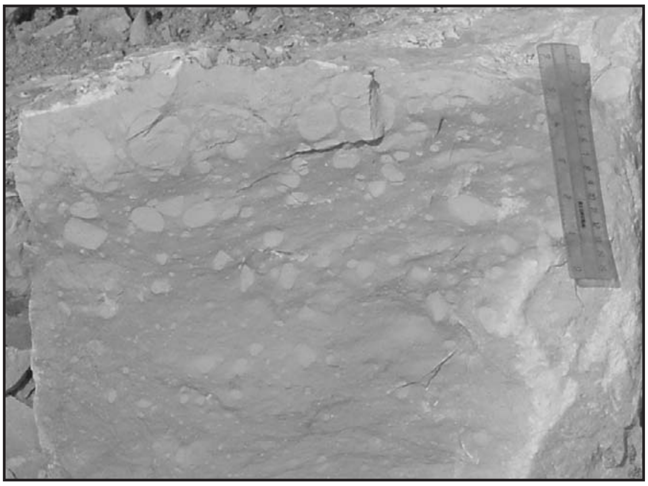

Figure 9. *Conglomeratic limestone from the upper part of Langport Member, in the Southam Cement Works Quarry. (SP419629) Ruler is 150 mm long.*

Conclusions

Much of the Triassic outcrop corresponds to three depositional settings generated through Permian to Early Triassic extensional reactivation of major basement faults. These are the Hinckley and Knowle Basins separated by the Coventry Horst. Triassic sediments are thinner on the horst, which preserves a depositional margin of the Knowle Basin in the Nuneaton inlier. The Triassic System in Warwickshire exemplifies the principal overall fining-upward facies development documented throughout southern Britain. The pebbly and arenaceous Sherwood Sandstone Group, deposited mainly in semi-arid fluvial settings, is overlain by the predominantly argillaceous Mercia Mudstone Group, comprising red-beds with subordinate sandstones. The Mercia Mudstone provides evidence for hot, arid, subaerial and subaqueous deposition with both freshwater and marine influences. Sparse macrobiotas from both groups provide evidence for terrestrial and subaeqeous habitats. The overlying Penarth Group confirms a Late Triassic marine transgression, heralding establishment of open shelf environments in the Early Jurassic.

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The Asian Tsunami, 2004

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Abstract. Displacement on the convergent plate boundary off the coast of Sumatra, late in 2004, created an earthquake of Magnitude 9.3. Uplift of the seabed generated a tsunami that swept the coasts of Sumatra, Sri Lanka and elsewhere round the Indian Ocean. Though the death toll and destruction were catastrophic, the value of any future warning system may be open to debate.

The tectonic event off the coast of Sumatra, very late in 2004, could be dismissed as a normal feature of a convergent plate boundary. Or it could be described as a very large earthquake, an unusual tsunami and a massive disaster (Fig. 1). Both views are correct. This is one geological event that everyone has heard about; it has had a significant impact on popular perceptions of earthquakes and tsunamis, and has already increased understanding in seismological science.

The earthquake

In the broad picture, the earthquake was due to fault displacement within the convergent boundary zone between the India oceanic plate and the Eurasia continental plate. The India plate is almost locked into the Eurasia plate where the Indian continental slab grinds into the Himalayas, but its movement increases towards the east. There it is subducted under the continental margin at Sumatra at a rate of about 60 mm per year, though this is locally oblique, in a direction about 45° to the plate boundary (Fig. 2). The plate boundary is marked by the Sunda Trench, with water more than 5000 m deep, where the main thrust fault dips at about 11° from its floor to lie beneath the continental shelf of Sumatra. Subduction of the oceanic plate is also marked by the line of 35 volcanoes along Sumatra and two more in the Andaman Islands.

The situation on the over-riding plate is complicated by the Burma microplate that lies between the Sunda Trench and a divergent boundary of only modest current activity beneath the Andaman Sea. East of this the Sunda plate is effectively the southern tip of the Eurasia plate, the two separated by a boundary of minimal movement.

Centuries of continuing subduction of the Indian plate (since any previous large earthquake in this sector) had dragged the Burma microplate downwards and also placed it in considerable compression. Strain energy steadily accumulated across the fault until, inevitably, it overcame the frictional resistance - early on December 26 when the rocks sheared along the fault plane. The initial failure was at a depth of about 30 km, beneath the shelf about 50 km off the coast of Sumatra, and the peak displacement along the fault plane was just over 20 m. This movement propagated outwards, and within about three minutes most of the southern half of the Burma microplate (as far as the Nicobar Islands) had moved by at least 10 m, with smaller displacements that extended and declined further north. Abrupt fault-plane displacement of 10 m or more extended across an area that was more than 400 km north-south and around 100 km wide. The direction of the fault movement (and therefore the tsunami impulse) was at 90° to the orientation of the plate boundary; this was about 45° from the direction of oblique plate subduction in this sector.

This huge extent of rock fracture accounted for the exceptionally high magnitude of 9.3. The very large stress accumulation, and therefore the very large earthquake, may have been in part due to constraint of the plate's oblique deformation within the curvature of the plate boundary. This could be a feature of the change of the Indian plate margin from convergent along the Sunda Trench to conservative strike-slip northwards through Myanmar. Stress may also have been increased by the epicentre's position just across the Sunda Trench from its junction with the poorly defined oceanic boundary between the India and Australia plates.

Figure 1. *The tsunami advancing on Khao Lak beach, Thailand, with a wave front that towers about 5 m above the single person in view. These images were recovered from the digital camera of a Canadian couple, John and Jackie Knill, who both died in the event; they have been made available by courtesy of the family.*

Earthquake magnitude

As an absolute scale of an earthquake's strength, the familiar Richter scale of earthquake magnitude has been superceded. Richter's scale is derived from wave amplitudes recorded on seismographs, but is not very precise, especially for large earthquakes. The newer Moment Magnitude scale is the measure of total energy released by an earthquake.

Seismic moment (M_O) relates to the fundamental parameters of the faulting process, as it is the product of the shear strength of the faulted rock, the area of the fault and the average displacement on the fault. Moment Magnitude (M_W) is then calculated as a logarithmic function of seismic moment, with constants introduced to give values that are close to Richter magnitudes (ML).

The Sumatran event is described as Magnitude 9.3, meaning the Moment Magnitude and not the Richter Magnitude. Magnitudes remain distinct from Intensity (either Mercalli or MSK), which reflects earthquake damage at an individual site, and therefore decreases away from the epicentre.

Tsunami magnitude is a log scale related to wave height and distsnce from source, which may or may not include a constant that makes it close to the earthquake magnitude.

Because it was under the sea, the earthquake had little direct impact on built structures. The nearest large town was Banda Aceh, on the northern tip of Sumatra, where the intensity reached VIII on the Mercalli scale. This was expressed in modest (but not total) damage to brick and concrete structures, along with various side effects - all of which were lost within the immediately subsequent tsunami destruction. Most timber buildings probably survived the earthquake very well, but were the most easily lost to the tsunami.

Even though damage intensity was low, this was a very major earthquake. An event of this magnitude is close to the theoretical maximum (which is based on the amount of stress that can accumulate in rocks before their shear strength is exceeded), and is due to the very large area activated on the fault plane. The Sumatra event ranks as the world's second largest since 1900 (Table 1); magnitudes of earlier events can only be roughly estimated. It is noticeable that the other earthquakes greater than Magnitude 9 have all been around the Pacific margin.

Within the following two weeks, there were more than a dozen aftershocks with magnitudes of 6-7, and an eventual total of around 600 smaller aftershocks. All were caused by stress redistribution within the Burma microplate, mainly north of the epicentre and reaching as far as the Andaman Islands. This continued slow slip extended the fault's rupture zone until it was 1200 km long. A full month after the main event, a distinctly separate swarm of aftershocks developed along a 20 km zone east of the Nicobar Islands (Fig. 2). This was due to movement of the Burma microplate against the Sunda plate, expressed in strike-slip displacements on the boundary fault.

Another earthquake, of Magnitude 8.7, followed on March 28, 2005, with its epicentre further south on the same plate boundary (Fig. 2). Though this was a major earthquake in its own right, it was effectively a large aftershock, as it was almost certainly triggered by stress changes during and after the December event. It caused significant destruction on the islands of Nias and Simeulue and on smaller islands between them, and some hundreds of people died. Though it created nearly 1 m of uplift on Simeulue and a similar amount of subsidence on one of the smaller islands, it developed only a very modest tsunami that reached a height of about 400 mm on the Sumatran coast.

Residual ground movement

The fault displacement of around 20 m was largely accounted for by relaxation of the Burma microplate as it moved outwards and upwards along the thrust plane over the Indian plate, which was relatively immobile in the short term (Fig. 3). With the fault plane dipping at 11°, this created the 4 m of seabed uplift that very effectively created the tsunami. This pattern of plate relaxation matches that first recognised after Alaska's earthquake of similar style in 1964, where large zones of both uplift and subsidence were measured in and around Prince William Sound. Modelling of ground displacements on the basis of the 2004 seismic data indicates a bowl of tectonic subsidence more than 1 m deep over the relaxed ground above the deeper part of the thrust fault and behind the frontal zone of uplift.

Reported observations after the event have confirmed the theoretical pattern of ground movement, though accurate survey data is not yet available. Simeulue, the most northerly island off the Sumatra coast (Fig. 2), was on the axis of rotation. Its west coast was elevated by about 1.5 m, exposing large areas of coral reef, while its east coast subsided by about 0.5 m, leaving land areas permanently flooded. The bowl of subsidence extended to the Aceh coast, parts of which declined by about 0.4 m. The zone of uplift extended west of the island, so was largely beneath the sea. Reports of large areas of newly exposed reef on the western sides of some of the Nicobar Islands, with flooded land on their east sides, indicate a similar pattern of residual ground movement. It appears that the zones of uplift and subsidence extended the full 1000 km between Simeulue and the Nicobars - accounting for the great size of the resultant tsunami.

earthquake location	year	M
Southern Chile	1960	9.5
Sumatra, Indonesia	2004	9.3
Southern Alaska, USA	1964	9.2
Aleutians, Alaska, USA	1957	9.1
Kamchatka, Russia	1952	9.0

Table 1. *The world's largest earthquakes since 1900; M = Moment Magnitude.*

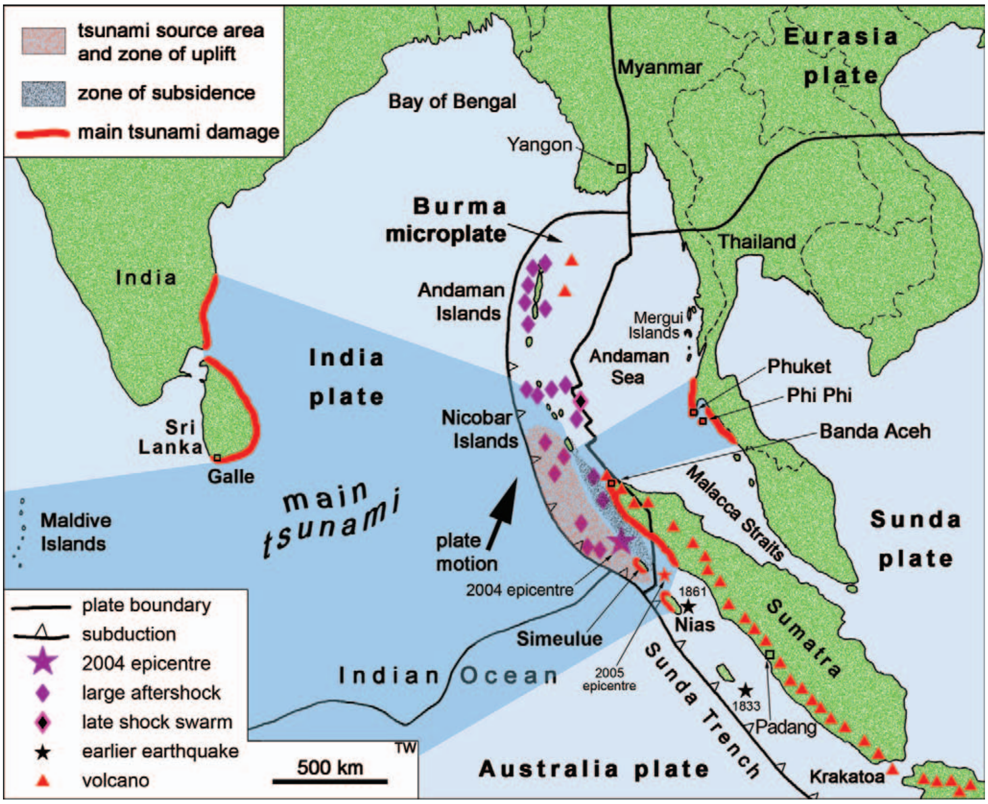

Figure 2. Locations of features of the 2004 earthquake and tsunami; the zones of subsidence and uplift are approximate, based on available observations and measurements; the areas swept by the main tsunamis have diffuse margins where wave heights decreased laterally.

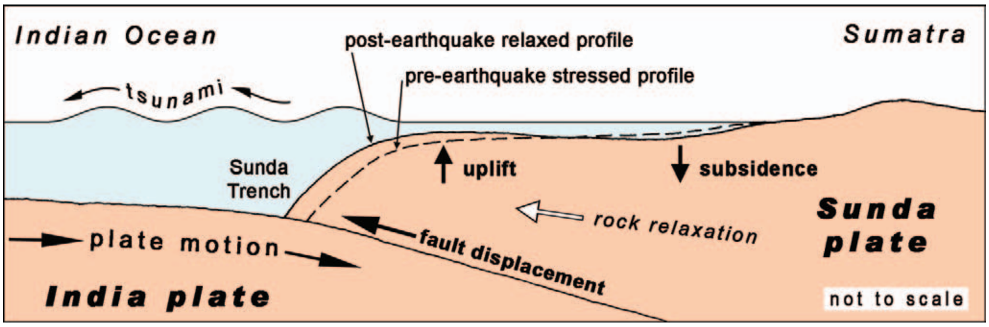

Figure 3. Schematic cross section through the earthquake zone; not to scale.

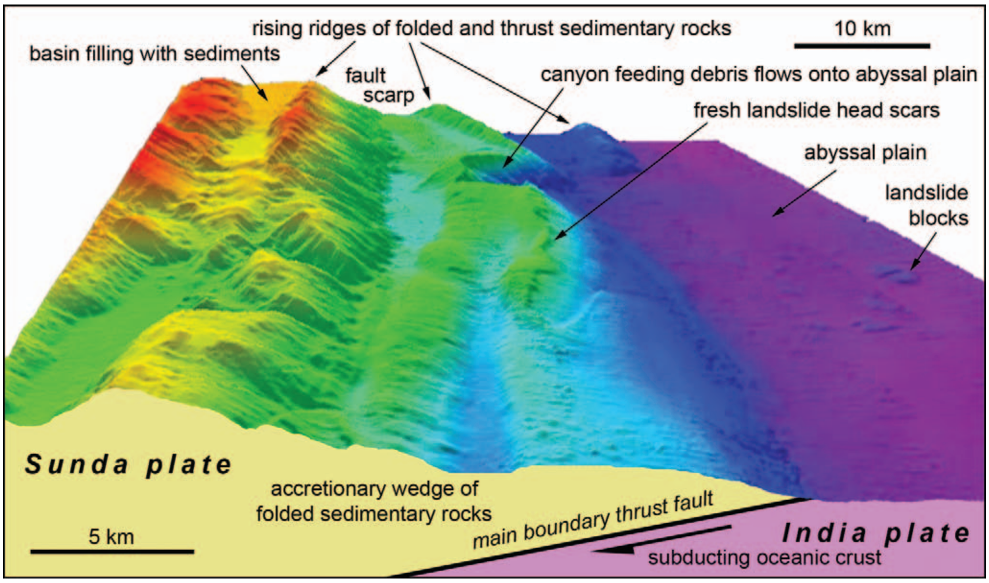

Figure 4. Seabed topography off the Sumatran coast, just west of the earthquake epicentre, looking southwest along the plate boundary; bar scales relate to the near and far ends of this very oblique perspective view; seabed colours show their depth, from red at about 1 km to purple at about 6 km; there is no vertical exaggeration. (Source survey by MHS Scott, by courtesy of the Royal Navy and U.K. Hydrographic Office.)

The marine survey conducted soon after the earthquake event could not detect the few metres of seabed uplift, but it did provide some spectacular images of the plate boundary, where the continental slope rises from the abyssal plain on the inbound oceanic plate (Fig. 4). Ridges up to 1500 m high and parallel to the fault scarps are interpreted as rising fold structures, with or without thrusts, within the wedge of sedimentary rock that is accreted to the front of the over-riding plate. Massive underwater landslides are also recognisable. Older slides have degraded into bowls at the head of canyons that fed debris flows onto the abyssal plain, while younger landslides are identified by their clean and un-eroded head scars. Some frontal ridges could be either folds or massive, old landslide blocks. Without resurvey before and after the earthquake, it is not clear how much movement or reactivation of all or parts of these slides and folds occurred during the 2004 event. Any sub-sea landslides of these sizes could contribute to the tsunami growth, in the same way that seabed uplift may be due to rising fold structures or a broader relaxation expansion of the continental plate edge.

The tsunami

Incorrectly known as a tidal wave, and oddly known by the Japanese word for a harbour wave, a tsunami is quite simply a very large wave that has been pushed by some large-scale rock movement. The largest tsunamis are created by abrupt seabed displacements of fault blocks, though they can also be created by volcanic explosions, or landslides under or into water.

Seafloor displacement pushes the water into a single large wave, which is then followed by oscillations as the water returns to equilibrium. The cyclic disturbance of the water means that, in far-travelled wave trains, the first wave is not usually the largest, because the second or third waves have resonated to greater heights; in 2004, this was recorded at most coastal arrivals. It also accounts for the frequently observed retreat of the sea in advance of the first positive wave, as water is sucked back into the growing wave; the frontal negative wave can also be enhanced by any seabed subsidence, as observed in the eastbound tsunami in 2004. Though waves radiate out in all directions, a tsunami wave is noticeably directional, with its greatest size being in the direction of fault displacement – westbound in the 2004 event.

Tsunamis are pressure waves developed through the entire depth profile of the water; they are unlike the rotational movements in surface waves created by wind. They therefore travel fastest when unimpeded across the open ocean, at speeds up to 800 km/hour, but are much slower where restrained by drag over the seabed in shallow water. A tsunami does weaken with distance from its source due to lateral dissipation of energy as the wave radiates over an enlarging front, though the long wavelength means that amelioration is much less than that of normal storm waves.

Felt in Britain and the East Midlands

Sumatra's massive earthquake was recorded on instruments all round the world. The seismograph at Melton Mowbray detected the first P-waves 25 minutes after the event, and the larger surface waves arrived around 2 a.m. local time, an hour after the event but still before the tsunami hit the Sri Lankan and Thai coasts.

Disturbance from the tsunami spread into every ocean of the world. After traversing the entire Indian Ocean and then the full length of the Atlantic, it arrived on Britain's shores about 37 hours after the event. It was barely recognisable on the tide gauge at Newlyn, in Cornwall, as its waves were less than 100 mm high and arrived almost on the crest of a storm surge that was significantly greater.

In the open ocean, a tsunami may be only 300 mm high (and unnoticeable to shipping), but it can pile up into a massive wave as it approaches land. This is due to the wavelength of 100 km or more, with the front of the wave slowing down in shallow water, while the rear catches it up. The effect is compounded as the wave crest overtakes the dragging wave base to create a towering breaker, and a wave further gains height where it is compressed into a tapering inlet. When the front of such a long wave steepens on approach to land, the profile becomes that of a great plateau. Its advance creates not a quick rise and fall of the water (as on a normal surfer's wave), but a sharp rise, followed by the water keeping on coming for 10 minutes or more. It is the sheer volume of water sweeping over a low coastline that causes the massive damage on land.

The 2004 tsunami was generated between Sumatra and the Nicobar Islands where the southern half of the Burma microplate was uplifted over the thrust fault (Fig. 2). It appears that the deeply buried fault at the earthquake epicentre was no more effective at tsunami creation that the zone at shallower depths into which movement propagated northwards. The huge area of uplift accounted for the great size of the tsunami, and the direction of fault movement launched the main tsunami crest on a compass bearing of 250° westwards towards the open ocean. Once started, the wave motion keeps on going, and the 2004 tsunami was recorded right across the world.

This was a very big tsunami. There are few reliable yardsticks for comparison of tsunami events because the wave impact on coastlines varies so much with respect to orientation, shape and profile. Wave heights reached on the nearest coast in the 2004 event appear to have had a general crest at about 15 m, excluding some very small tapering inlets where wash certainly went much higher. The tsunami from the eruption of Krakatoa in 1883 is commonly credited with wave heights of 30 m, and there have been some very high tsunamis impacting the coasts of Japan in historical times, but the 2004 event does appear to lie in the top handful of the world's earthquake tsunamis.

This excludes localised events such as the landslide-created wave in Lituya Bay, Alaska, that achieved a run-up to around 500 m above sea level in 1958. Nobody died at Lituya Bay, because nobody was there, but if tsunamis are judged by the numbers of people they kill, then the 2004 event that emanated from Sumatra was the world's worst.

Tsunami impact in the source area

On all unprotected, low-lying coasts the impact of the tsunami was the same. It swirled inland as a relentless flood of seawater; it developed bores a few metres high in river channels, inlets and valleys, but elsewhere it was a smoother rise of water level. Even though it lacked the drama of towering waves except on a few exposed beaches, the water swept relentlessly inland until checked by higher ground. The effect was rapid flooding, and the surges moved faster than a man could run. Water velocities were up to 30 kph, so high that people had little chance of swimming to safety, and structural damage was widespread. The soft sediments of coastal plains were easily scoured, and the backwash of the retreating tsunami scoured huge volumes of sand and mud to leave the ground surface below sea level. Added to this was the tectonic subsidence of about 0.5 m; swathes of coastal Sumatra were transformed from low land to shallow sea.

The city of Banda Aceh, in northern Sumatra, was the nearest to the earthquake epicentre. Many of its smaller buildings collapsed, but the effects were eclipsed 15 minutes later when the tsunami arrived. Wave heights reached 10-15m on many parts of the western coast of Aceh province, creating massive damage as the sea swept kilometres inland. Large ships were thrown up on shore, and harbour walls were smashed and undermined. Houses, bridges, trees and crops were stripped from low-lying areas as far as 3 km or more inland, bays and inlets were enlarged by scour, but hills between escaped unscathed (see the back cover for 'before' and 'after' images of Gleebruk on the Aceh coast; from NASA Earth Observatory).

Within 30 minutes the tsunami had hit the Nicobar and Andaman Islands. Wave heights reached over 5 m, and many people died on the low-lying islands, but the impact was minimised by the steep profiles of the volcanic islands within the chain.

Off the coast of Sumatra, the villagers of Lewah, on the island of Simeulue (Fig. 2), had experienced shaking from the earthquake so strong that for two minutes nobody could stay standing. But they then ran to the adjacent hills, so nobody died when the tsunami arrived soon after. On Nias, the next island south, the north-coast town of Lahewa was hit by a series of tsunami waves; of these, the third arrived as a surge nearly 2 m high over 5 hours after the earthquake. These appear to have been reflected waves, as was the one that swept up the east coast of Nias from the south nearly 8 hours after the earthquake.

The Indian Ocean tsunami

The tsunami crossed the Bay of Bengal in just two hours, to launch its major impact on the unprotected coasts of southeast India and eastern and southern Sri Lanka. A sequence of three waves reached heights of 5-10 m where the tsunami swept up onto open sand beaches and washed inland across very low gradients. Some coastal towns were just seriously flooded (Fig. 5), but many villages on the exposed west coasts of Sri Lanka and India were simply wiped off the map. Basic wooden buildings that faced tropical beaches were fine for anything except a tsunami wave when water rose just a few metres to destroy everything. In many villages, only the fishermen survived because they were out on their boats in deep water, where the tsunami passed unnoticed beneath them.

The worst single tragedy overtook a crowded train on the coastal line to Galle, in southern Sri Lanka. The first tsunami wave derailed the train and caused few casualties, but left its passengers stranded and exposed to the full force of a second, larger wave. This swept in 3 m deep onto the overturned carriages; only 20 people survived out of 1500 on the train.

The southwestern sector of the tsunami swept past Sri Lanka, but then lost much of its energy as it spread out into the western Indian Ocean. It caused major flooding on the low-lying Maldives and Seychelles, but had less remaining power by the time it reached the African coast. Fortunately, there were few people living along the Somalian sector which received the greatest impact.

Disaster-prone Bangladesh escaped lightly from this one. The tsunami had little northward component, and then lost energy in crossing the huge deltaic apron of sediment within the north end of the Bay of Bengal, before meeting a braided coastline with only a low population; just two children died when a small boat was capsized by the reduced tsunami wave.

Figure 5. *Tsunami water sweeps the streets of a small town on the south coast of Sri Lanka (photo: NBC).*

Figure 6. *Damage to a car left beside a Phuket beach show why so many people died when they were swept into the debris-laden tsunami inrush (photo: Liz Price).*

The Andaman Sea tsunami

The rebound effect of wave surges meant that the tsunami's second greatest development was eastwards, through the deeper channel south of the Nicobar Islands, and on towards Thailand. The shallower water in the Straits of Malacca meant that it travelled more slowly than in the ocean, and it took two hours to reach the unprotected Thai coast around Phuket, where wave heights were generally around 3 m. Some beach profiles created breaking waves that were over 5 m high (Fig. 1), and tree damage around some tapering inlets on the rocky sections of coast showed that the tsunami washed up to about 25 m high.

Unfortunately, the tsunami hit Phuket and the coast just to the north on the crest of a high tide and in mid-morning, by which time the beaches and towns were crowded with holidaymakers. Many people on the beaches could escape to high ground when they saw the abnormally large waves approaching; the second wave (15 minutes after the first) was the largest, and some people even took warning from the sea's retreat just prior to arrival of the first wave (there was a frontal trough to the tsunami wave chain in this direction). But there was less warning in the towns; when debris-laden seawater swept through 1-2 m deep, and fast enough to wash all the cars out of the streets, people caught at ground level had to be lucky to survive (Fig. 6). The upper floors of modern hotels were safe, as most concrete buildings survived, but wooden buildings were wrecked (Fig. 7). The wave impact varied greatly from beach to beach, being greatest where the beach had a gentle profile or faced directly to the west.

The tsunami lost only some of its power as it swept into Phang Nga Bay, and the island of Phi Phi had its sea-level town washed away while the limestone hills remained uninhabited and unscathed. South of Phi Phi, the tsunami hit Ko Mook while a group of 80 tourists were swimming through the sea-level Emerald Cave into the hong (a doline lagoon inside the limestone island); two died in the water surge through the cave, while the rest survived by climbing onto rock ledges.

Towards the northeast, the official death toll in Myanmar was only 90, but reports from that country are unreliable due to the military censorship. The tsunami may have lost energy in the shallows of the Andaman Sea, but it must have had significant impact on the Mergui Islands and mainland coast of southern Myanmar; the fate of many of the Moken sea gypsies who live round the islands may never be known. There are also reports of hundreds of people drowned when villages of shanty houses were destroyed along the coast west of Yangon.

Figure 7. *Concrete buildings survived in Phuket, Thailand, but the ground floors of frailer structures were washed out by the swirling tsunami waters (photo: Liz Price).*

Figure 8. *A seaview bar in Phuket re-opens while still bearing a reminder of the tsunami (photo: Liz Price).*

The aftermath

By March 2005, the death toll of the earthquake and tsunami had risen to around 290,000, and nearly all of these died in the tsunami as opposed to in the preceding earthquake. With many people still listed as missing, and many bodies carried out to sea, the final toll may be close to 300,000.

With so many people washed away by the tsunami, the immediate desperate task for so many survivors was to find missing relatives. Then, reunited or not, survival became the major task. Drinkable water was a rare commodity, food was nearly non-existent, and only the warm weather made the lack of shelter just tolerable. There was concern that the many dead bodies and vast amounts of debris constituted a major health hazard, but there was no significant outbreak of disease after the event. Estimates gave half a million people injured, a million homeless and five million without access to basic services; the subsequent international aid effort was unprecedented.

Rebuilding and protection

Repairs to water supplies, roads, bridges and hospitals were immediate tasks for the state agencies. Rebuilding of houses and homes largely falls to the struggling survivors, and therefore has a certain delay, which could give time for better planning. There would be clear benefits in rebuilding some of the towns and villages on higher ground, where topography permits. Elsewhere, coral reefs, coastal mangrove forests and sand dunes could protect future development; positive conservation or even their re-establishment would be worthwhile, as shown by some protected sites in 2004. Beach hotels and fishing villages may be increasingly recognised as undesirable, though tourism is vital to the economy of many coastal regions (Fig. 8).

Press criticisms of inadequate building standards were not justified; the simple wooden houses in most regions were perfectly satisfactory for anything except the exceptional. Especially without the luxury of a Western economy, it is unreal to design structures to withstand events that occur only at intervals of hundreds of years. Most concrete structures survived the tsunami. But the villages of Sumatra had few of these other than the mosques - which remained after the event like giant tombstones amid oceans of debris. Where a town has to be rebuilt on low ground, a scatter of concrete buildings three storeys high could offer valuable refuges in any future tsunami; large tourist hotels could be a real benefit in this respect.

Predictions and warnings

The more significant aftermath debate is over the scope for predicting or warning of a tsunami. Sadly, prediction is impossible; the causative earthquakes cannot yet be predicted. Furthermore, not all undersea earthquakes produce tsunamis, and an event can only be recognised on tide gauges once it has started. So the alternative is a warning system. The Pacific Ocean has 90% of the world's tsunamis, and already has an international tsunami warning system in place. Offshore earthquakes are detected, and signs of tsunamis are then monitored. Tsunamis can only be seen in shallow coastal waters, but automated tide gauges and seabed pressure gauges record the passing of low and long tsunami waves in open water. Serial warnings are then issued, though how a tsunami affects a distant coast varies with local conditions.

No such system exists for the Indian Ocean. Proposals for one had been discussed by the relevant coastal nations prior to the 2004 event, but had been shelved or dismissed as not worthwhile. Even with hindsight, this appears to have been a reasonable decision. There have been very few tsunamis in the Indian Ocean. The Sumatran coast suffered destructive tsunamis in 1797, 1833, 1843 and 1861 (besides the Krakatoa event in 1883), but there was none in the 20th century.

However a United Nations meeting on Disaster Reduction, coincidentally held in January 2005 in Kobe, Japan, did resolve to establish an Indian Ocean tsunami warning system by mid-2006. Plans for effective response, including education programmes in tsunami-awareness, would take another few years, and there are even plans for a global system by 2007. Kobe's budget for this was $30M, but how this was to be raised was not answered, and India has since estimated a budget of $27M just for its input. There must be serious questions about the benefits of such a programme; it appears that emotions and politics could have overtaken reality at Kobe.

Even if a system is in place, warning times could be minimal. Scientists at the Pacific Tsunami Warning Centre in Hawaii knew of the 2004 earthquake within minutes of it happening. But it was a few hours before they knew its size and could assess the tsunami hazard. By then, 80% of the tsunami casualties were already dead. And they could find nobody to warn of the danger, other than the US base on Diego Garcia. They did manage to contact Kenya, where some coastal evacuation was then organised, so that only one person died when the reduced tsunami hit the coast eight hours after the earthquake.

A well-established Indian Ocean system would not have had enough time to give any useful warning on Sumatra, where the majority of the casualties occurred. Towns in Sri Lanka and Thailand could have been warned, but time would have been very tight. And warning a coastal villager, who is too poor to buy batteries for his transistor radio, is seriously difficult. Tsunamis take 10-20 hours to cross the Pacific Ocean. A future tsunami further south along the Sumatran coast will hit the city of Padang within 10-20 minutes. No high-tech system will provide enough warning before a 2 km run-up (as seen this time in Aceh), devastates a Padang city much larger than when it was heavily damaged by a tsunami in 1833.

Realistic warning may be garnered from local sources better than from an expensive international system. While human bodies littered the tsunami debris in both Sumatra and Sri Lanka, there were very few other large animals. No elephants died in Sri Lanka. They and many other animals can detect low-frequency ground and air vibrations (generated by an earthquake or an approaching tsunami). A seismic signal is a type of acoustic vibration. If it is greatly magnified, it can be heard by man; but its low-amplitude, low-frequency can be heard by animals, and their natural senses tell them to move away from danger. It was widely noted that animals moved inland to safety before the tsunami struck. Aboriginal peoples, who live on isolated islands in the Nicobars, suffered minimal casualties; there is no evidence that they have any sixth sense, but they noted changes in bird calls, and then just followed their animals up onto high ground – before the tsunami arrived.

Perhaps tsunami-awareness programmes could be more cost-effective than high-tech science. Knowing about the almost ubiquitous sea retreat ahead of a tsunami, and watching the animals, really does work, even on coasts adjacent to an offshore earthquake epicentre. And the money saved could be spent on some tsunami-proof concrete buildings.

In context

The 2004 Asian earthquake tsunami was a major disaster; and was by far the world's worst tsunami event. The only two earthquakes that may have been more disastrous were both in China, with data that is old or perhaps unreliable (one in 1556 with 830,000 dead, and one in 1976 with a toll widely reported as 655,000). Disease and flooding have taken greater tolls, but there is something dramatic and immediate about earthquakes and tsunamis. However, one of the reasons for the high number of deaths in the 2004 tsunami was quite simply the vast numbers of people now crowded onto planet Earth, and few areas are more crowded than the shores of the Indian Ocean. Each major event tends to be worse than the last one.

It is perhaps relevant to look at the numbers of people that die as a proportion of the contemporary world population (Table 2). It then appears that, awful and tragic though it was, the 2004 tsunami was overshadowed by the great earthquake in China. It was also quite minor in comparison to the effects of influenza and the plague. It was trivial in comparison to malaria, which may have killed half of all the people that have ever lived. And its death toll is matched about every 10 days by those who die of starvation, mostly in Africa.

A British tsunami?

The chances of a tsunami hitting Britain are very low indeed, but are not zero. An earthquake-induced event is very unlikely, mainly because the Atlantic Ocean has only a short section of convergent boundary, with minimal activity, flanking the Caribbean Antilles. In 1755, the seabed earthquake, off the Portugal coast, created massive tsunami damage in Lisbon and elsewhere on the nearby European and African shores. The tsunami reached the coast of Britain as a wave train that lasted nearly 5 hours, with the third and fourth waves each about 3 m high at Newlyn, Cornwall, but the overall impact was little more than that of a storm surge on a spring high tide. There was also the probable tsunami in the Bristol Channel in 1607 (see *Geobrowser* on page 74 in this issue of the *Mercian*).

The greater threat comes from landslide-induced tsunamis. The gigantic slide of seabed sediments at Storegga, in the northern North Sea, created a tsunami that swept the coasts of Scotland and Northumbria about 8000 years ago (*Mercian*, v15, p5; David Smith, 2005, *Geology Today*, v21, pp64-68). Threat of an Atlantic tsunami from a future collapse of the Cumbre Vieja volcano in the Canary Islands is recognised, but this does rely on a rapid large-scale failure; the alternative of slow sliding or small multiple failures will have much less impact. More seabed debris flows are being recognised (*Mercian*, v15, p4), so the tsunami hazard does exist, but the risk is reduced by the extreme rarity of these events.

The one benefit of a great tragedy is that it unifies people in fighting a common cause. After the 2004 tsunami, armed opponents overcame their differences, and everyone helped the injured and bereaved. But the ceasefires lasted only days. Then, the Indonesian army and the Aceh rebels resumed killing each other, some high caste Indians refused precious water to low caste villagers, and fighting resumed in Sri Lanka's 20-year war with the Tamil Tigers – which has killed nearly double the tsunami toll. These facts should all be significant to any over-reaction towards creating an expensive tsunami warning system in a part of the world that has far greater problems to resolve.

Acknowledgements

Parts of this text and the map have been adapted and updated from an earlier version in Geology Today (v21, p22-26, January 2005), and appear by kind permission of the editor. Parts of the report have been compiled from data gathered and analysed by the U.S. Geological Survey (www.earthquake.usgs.org) and by the Tsunami Laboratory in Russia (www.tsun.sscc.ru). Thanks also to Philip Woodworth for tide gauge data, Liz Price for her photos, and John Carney for helpful comments during preparation.

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event	date	deaths	world population	proportion of mankind killed
tsunami, Indian Ocean	2004	>290,000	6000M	0.0048 %
earthquake, Shanxi, China	1556	830,000	500M	0.17 %
influenza, worldwide	1918-19	21,000,000	2000M	1 %
plague, Black Death	14th C	75,000,000	400M	20 %

Table 2. *Natural disasters of the world, in context.*

Glacial Geology of the Condover Area, South Shropshire

Peter Worsley

Abstract. Late glacial mammoth remains were discovered during the extension of the Norton Farm sand and gravel quarry at Condover. At the Last Glacial Maximum a northern derived ice sheet terminated 15 km south of the quarry site. Many large blocks of glacial ice were buried in the associated outwash and till. An advance of Welsh ice terminated at Shrewsbury, 5 km to the north. Following this, regional deglaciation occurred, and localised, complex, dead-ice terrain developed with many kettle holes. Ice marginal lakes progressively drained and the ancestors of the present river systems developed on the glacial deposits. The kettle holes acted as sedimentation sinks. In the early Windermere Interstadial, lush vegetation on the floor of the Norton Farm kettle attracted mammoths, which then became trapped in the unconsolidated fills. Subfossil mammoth bones were discovered in 1986 when a kettle fill at the Norton Farm quarry was excavated.

Condover rose into the national limelight in late 1986 after mammoth bones had been discovered by Mrs Eve Roberts on the evening of 27th September. They were found protruding from dumped overburden at an active sand and gravel quarry at Norton Farm. These were sensational finds. They formed the most complete adult male mammoth skeleton found in Britain so far, and their clearly late-glacial age pushed forward the mammoths' extinction by about 5000 years, to c12 ka BP, when relatively mild interstadial conditions prevailed.

The aggregate workings (at SJ494073) lie close to the village of Condover, 5 km south of Shrewsbury (Fig. 1). The site lies within an undulating lowland plain, which to the west, south and east is surrounded by higher ground on Precambrian and Palaeozoic bedrock. Northwards the lowlands are relatively unrestricted and extend beyond Shropshire through Cheshire to the shores of the Irish Sea. The River Severn crosses the south Shropshire lowlands from west to east, and passes 4 km north of Condover. Anomalously, the river fails to take advantage of a potential shorter low-ground route to the north, and cuts through the bordering rim of higher ground, via the Ironbridge Gorge, to eventually reach the Irish Sea by way of the Severn Estuary. This is probably the most spectacular glacial diversion of drainage of the Last Glaciation in Britain, and was first recognised by Charles Lapworth in the late 19th century. The last major right bank tributary to the Severn before the gorge is the Cound Brook, and this approaches to within 1 km of the mammoth site (Fig. 1).

Within the immediate surrounds of Condover the poorly exposed bedrock forms part of the Salop Formation, a sequence of Upper Carboniferous red sandstones and mudstones. They constitute part of the Leebotwood Basin succession, which is enclosed by major faults to the northwest and southeast, (Toghill 1990). Within the Cheshire-Shropshire lowlands, the youngest solid sequence is middle Jurassic, and a major hiatus separates it from the Quaternary cover succession. In south Shropshire, only the products of the latter part of the last major climatic cycle of the Quaternary are recognised at present. In formal stratigraphical terms the three climatic stages which contribute to the full cycle are the Ipswichian Interglacial (part), followed by the Devensian cold stage and then the Flandrian Interglacial that continues to the present time.

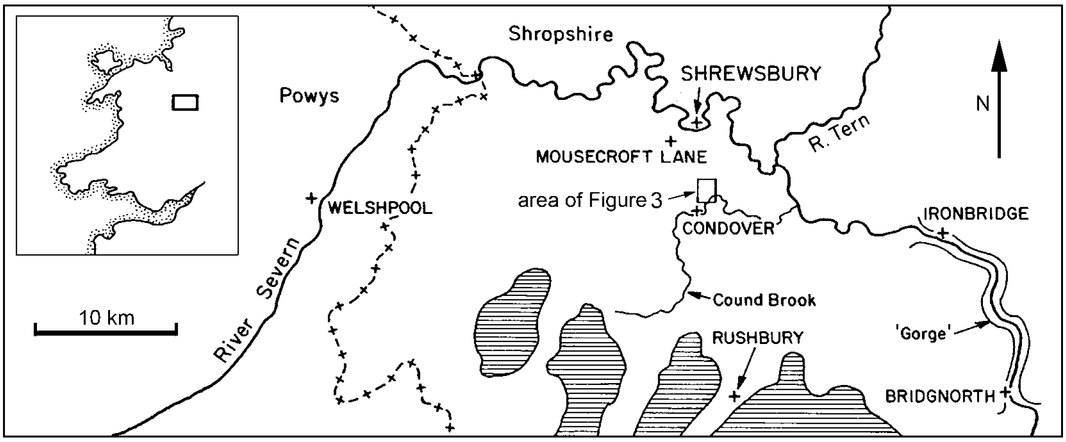

Figure 1. *Location of Condover and related adjacent sites in southern Shropshire. The shaded areas along the southern borders of the map lie beyond the maximum extent of glaciation at the Last Glacial Maximum (the Late Devensian). Based on B.G.S. mapping.*

The local Devensian sedimentary record is dominated by glaciogenic deposits associated with the Last Glacial Maximum ice advance and its subsequent retreat. This reached an advance limit around 15 km south of Condover (Fig. 1) (Greig *et al*. 1968), and probably culminated about 20 ka BP. Traditionally this is known as the Newer Drift limit, since within it, constructional glacial landforms are common and the amount of post-deglaciation erosion is limited; this contrasts with the Older Drift beyond, which is normally heavily dissected and devoid of constructional glacial morphology (Worsley, 2005). This outer area, beyond the ice advance limit was subject to prolonged periglaciation during the glacial stage; not all of it has older glaciogenic sediments and much of the higher ground in south Shropshire is directly underlain by bedrock. Effects of periglacial processes are the tors, stone polygons and allied stripes that formed on the Ordovician quartzites of the Stiperstones (Goudie & Piggott, 1981).

Sedimentary evidence for constraining the timing of the Last Glacial Maximum event in Britain is provided by the sequence that defines the Devensian Stage. Fortuitously this is located only 40 km east of Condover, at Four Ashes in Staffordshire. There the glacial sediments overlie locally derived gravels that ante-date the ice advance and the contained organics have yielded a minimum radiocarbon date of some 30 ka BP. Nearby, an organic-rich sequence post-dating the glacial advance at Stafford has yielded a radiocarbon date giving a youngest age to the ice withdrawal of 13.5 ka BP (Bartley & Morgan, 1990).

Glacial research in the Shropshire Lowlands

Undoubtedly the most valuable and detailed regional study of the Shrewsbury area glaciogenic sediments arose as part of the 1:10,560 geological mapping by the Geological Survey, which led to publication of the 1:63,360 Shrewsbury drift sheet 152, plus an accompanying memoir (Pocock *et al*, 1938). Although the field mapping was undertaken between 1914 and 1929, this work remains the benchmark study. Its value was enhanced by the geologists involved clearly having a personal interest in the interpretation of the glacial sediments and landforms.

Subsequently, Shaw (1971, 1972a, 1972b) made valuable contributions to understanding the glacial sedimentology in the context of an evolving appreciation of the complex nature of contemporary glacial depositional environments. An appraisal of sand and gravel resources by the Geological Survey (Cannell, 1982) covered two adjacent 1:25,000 sheets centred on Shrewsbury, and documented a large borehole data base. However, this did not extend as far south as Condover. This deficiency was largely rectified by a similar resource survey by the Engineering Geology Unit of Liverpool University (Crimes, 1985). The latter study covered an irregularly shaped area including Condover, but a tantalising strip, 2 km wide and aligned east-west, separated the two investigations. Although both Cannell (1982) and Crimes (1985) attempted some interpretation of their data, their brief was only to assess the bulk mineral resources. Nevertheless, in comparison with many areas of Britain there is a rich archive of sub-surface information pertaining to the glacial sediments of the Condover district.

Outline glacial history

The glacial stratigraphy has been interpreted in terms of two different ice advance events within a single glaciation (Pocock et al, 1938). The first was thought to have moved essentially southwards from out of the Irish Sea Basin, bringing with it erratic material derived from the granite and volcaniclastic outcrops in the Lake District and south west Scotland, with abundant sediment from the relatively soft Carboniferous and especially the Permo-Triassic of the Irish Sea borderlands. The resultant glaciogenic materials are red-brown in colour. A very minor but significant fraction also consists of a derived Pleistocene marine fauna from the bed of the Irish Sea (Thompson & Worsley, 1966). There are two radiocarbon assays on marine shells in the Condover vicinity, >38 ka (Birm-60) from Great Ryton and 32 ka (I-2939) from Buildwas. Both of these are consistent with the regional chronological picture. The second glacial advance was surmised to have originated within the Welsh Uplands and moved generally eastward through the borderlands, bringing

stage or sub-stage	event	sediments	beds in kettle hole	years BP
Flandrian Interglacial	Post-glacial		f & g	10,000
Loch Lomond Stadial			e	11,000
Windermere Interstadial			c (*with mammoth*) & d	*12,500*
Dimlington Stadial	Last Glacial Maximum	Shrewsbury Formation Stockport Formation	a & b	13,500 26,000
Middle and Early Devensian Glacials and Ipswichian Interglacial				

Table 1. *Correlation of events and sediments in the Condover area.*

with it various Palaeozoic lithologies (lavas, tuffs, limestones, sandstones and slates) that impart an overall grey colour to its till and outwash lithologies.

The relationship between these two ice advances in south Shropshire was excellently exposed in a former aggregate quarry at Mousecroft Lane in the southwest suburbs of Shrewsbury during the 1960-70s. Outcrop evidence showed that the ice derived from the northerly Irish Sea arrived first, and that the Welsh ice advanced after the Irish Sea ice had retreated from the site. The succession was first described by Poole and Whiteman (1961) although their specific interpretation found little support by other workers. A note by Shotton (1962) described a deep borehole adjacent to the quarry and Worsley (1991) included a log of a sequence 19 m thick exposed in 1964 beneath a kettle hole that had been cross-sectioned by the advancing quarry face (Fig. 2); this succession is dominated by fluvial facies. Shaw (1971, 1972a) elaborated on the sedimentology, and Worsley (1977) provided the last stratigraphic account prior to abandonment of the site. Two key relationships revealed at Mousecroft Lane were that ice blocks must have been entombed within the outwash sediments of the first (Irish Sea) ice advance, and that the bulk of the deformation and subsidence arising from the later melt-out of these blocks took place after the retreat of the second (Welsh) advance.

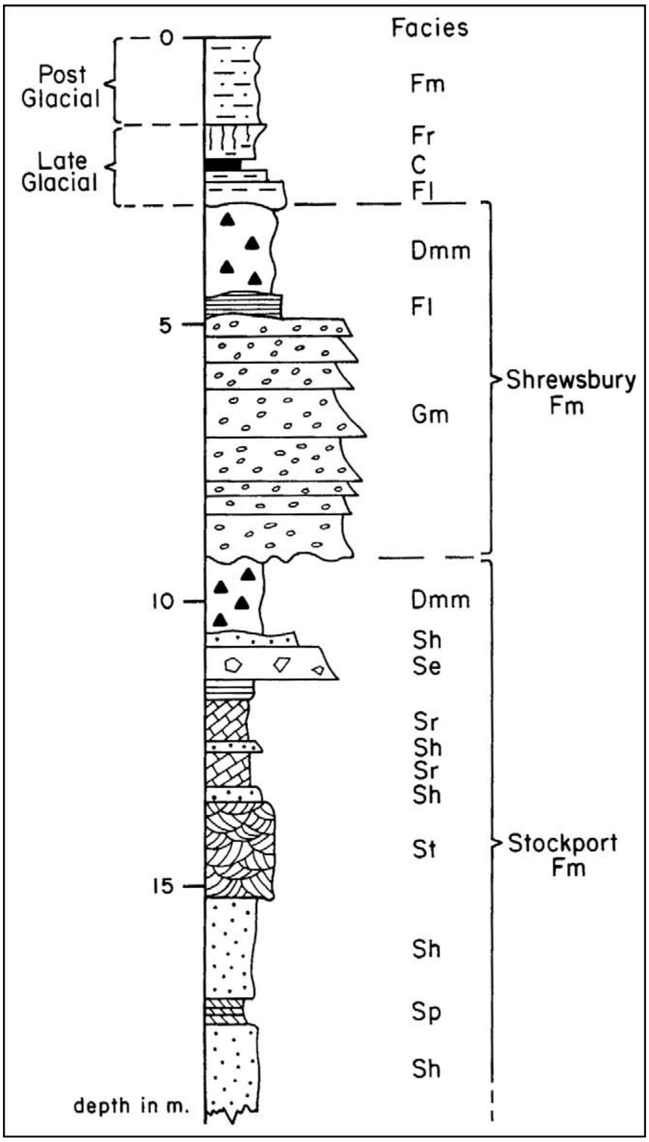

Figure 2. *Sedimentological log of the succession exposed at SJ 478109 in the Mousecroft Lane Quarry, Shrewsbury in 1964. The Stockport Formation consists of the products of the earlier ice advance from the north, whereas the Shrewsbury Formation represents the sediments introduced by a later ice advance from the west. Since this log lies directly beneath a kettle hole, the Shrewsbury Formation is overlain by kettle hole infill sediments of late and post glacial age. Lithofacies codes:- C = clay; F = fine silt: S = sand: D = diamict; c = angular clasts of sand; h = horizontally stratified; m = massive, matrix supported; p = planar; r = rippled; rs = roots; t = trough-bedded.*

More recently, Worsley (1991, 1999) has proposed that, since the earlier sequence derived from the Irish Sea can now be confidently regarded as the lateral equivalent of the Stockport Formation, it should be named as such, whereas the later succession of a till overlying its sandur is the Shrewsbury Formation.

The Norton Farm area

The area adjacent north and northeast of Norton Farm displays some of the most spectacular hummocky glacial terrain in England. It is not easy to describe the landform assemblage since specific forms grade into one another resulting in complex terrain. In general hummocks (kames) and linear features (eskers) are interspersed by hollows (kettles) on varying scales. The latter are generally interpreted as the sites of former buried glacier ice, and between and over them the glacial sediments (mainly outwash) accumulated. Later with climatic amelioration the ice melted to leave the kettle holes as elements of the present day relief. Many of these remain to be integrated into the modern fluvial drainage network. Northeast of the quarry, a major esker-like linear ridge of sand and gravels extends from Sharpstone Hill in the north west for about 1500 m, before it is cut by the valley of the Cound Brook. This ridge is bordered by linear depressions one of which is occupied by Bomere Pool, south of the farm (Fig. 3). The quarry is cut into a large, complex kame-like landform, the southeast portion of which still survives. Prior to its opening and the attendant destruction, it was reported that, at Norton Farm, *a hill of sand and gravel, with a very moundy surface, rises steeply from the fluvioglacial terrace on the north and north-west but gently from the boulder clay (till) area on the east* (Pocock *et al*, 1938).

Sharpstone Hill is a low ridge of Longmyndian grit that protrudes through the glacial cover. During the official geological survey, Pocock reported 'well marked striae' on freshly exposed surfaces, indicative of a north-south ice movement during a phase of net erosion associated with basal sliding. Eastwards, the sub-drift surface forms a broad shallow valley with an axis falling from southwest to northeast. Condover village lies over the valley axis, and Norton Farm Quarry is located over the northwest flank, where bedrock lies at around 65 m OD, whereas the present day land surface at the site averages 90 m OD. The degree to which the bedrock surface is modified by glacial erosion is unknown, but the valley morphology has nothing to suggest that the low ground was greatly influenced by ice erosion, in marked contrast to the resistant ridge of Sharpstone Hill.

The original operators of the Norton Farm Quarry (ARC Western) commissioned 70 exploration boreholes to establish the magnitude of the sand and gravel resource. Although these remain confidential, the compilers of the sand and gravel isopachyte maps and cross sections (Crimes, 1985: Figs. 14, 11 and 16) had access to them. That survey commissioned an additional six new boreholes, and the logs of these are in the public domain. An adapted version of the borehole data can be presented as a series of cross sections (Fig. 4). Thus stratigraphic data for the area around Norton Farm Quarry are unusually good.

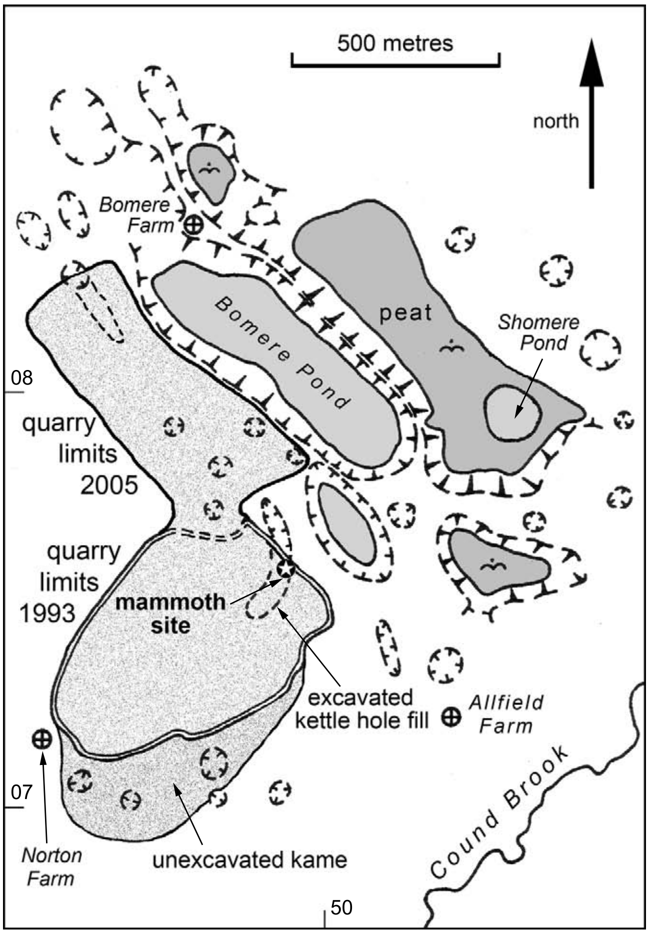

***Figure 3.** Glacial geomorphology of the area adjacent to the Norton Farm Quarry, Condover, to show the extent of the kettle holes and associated ice-contact features.*

Above the bedrock surface at Norton Farm, the glacial litho-stratigraphy is relatively simple, consisting of a lower till smeared over the solid such that its upper surface tends to mimic the rockhead profile. Above this, a major body of sand and gravel body is generally over 20 m thick, but is confined laterally by steep margins, giving the impression that it is set into the till beneath. In plan form this sediment unit is funnel-shaped, with the apex at Condover village and a long axis towards the northeast (Fig. 4). In places the sands and gravels crop out at the surface, usually as kame landforms. Associated with the kame areas are relatively thin till sheets which pass laterally into a much thicker till unit at the margins of the sand and gravel.

The initial quarry exposures were discussed by Shaw (1972b), based upon observations in the late 1960s. He described a complex sedimentary association with an upper unit consisting of a central gravel-dominated zone passing laterally into mainly horizontally stratified sands. These relationships, along with the occurrence of widespread faulting, encouraged him to suggest that initially the glacial meltwater depositional environment was constrained by glacier ice walls, then, upon melting, the removal of lateral support led to collapse in the ice-contact zone. A lower unit was interpreted as part of a deltaic sequence, with a longitudinal section of classical delta foresets dipping 30º to 210º. Levelling of the truncated top established that the water body into which the delta was prograding stood at a minimum of 81.4 m OD. Such a vertical change in sedimentary facies well illustrates the dynamic nature of the ice marginal environment with, in this case, ponded water deposition abruptly giving way to torrential river sedimentation.

Surface mapping of the distribution of enclosed hollows shows that they occur on a wide range of scales (Fig. 3). When their locations are superimposed upon the extent of the sand and gravel unit revealed by the boreholes, the virtual correspondence suggests a genetic link between the two. Significantly, this same relationship could be identified in the Mousecroft Lane area, in Shrewsbury. Hence, it appears that the sedimentological environments associated with the accumulation of the thick sand and gravel units were conducive to the burial of detached blocks of ice derived from the glacier; these were later to melt-out, and induce subsidence of their cover sediments.

All the available stratigraphic data suggest that the Shrewsbury Formation is absent in the immediate Condover area and that the glacial sediments *per se* all belong to the slightly earlier Stockport Formation. The latter corresponds to the Last Glacial Maximum, and this major glacial ice advance culminated at about 20 ka. The Shrewsbury Formation post-dates the maximum ice advance in south Shropshire; although the time differential is unknown, relationships indicate that there was no climatic warming between the two ice advances. The probability is that they were within a millennium of each other, and farther north along the Welsh border they were coeval. No local evidence is known to support the assignment of the deeper glaciogenic sediments to a pre-Devensian age, although this possibility should not be excluded.

‘Flood-gravels’ and glacial lakes

The Geological Survey officers' interest in glacial geology probably accounts for the adoption of a classification recognising two separate kinds of glacial meltwater deposits, 'glacial sand and gravel' and 'fluvio-glacial flood-gravels' on the Shrewsbury map sheet. The discrimination of the latter is not usual Survey practice. According to T.H. Whitehead (in Pocock *et al*, 1938, and pers. comm., 1965), the flood gravels were envisaged as being produced by 'torrents of water, perhaps derived from the melting of snow on the hills' washing coarse detritus to form valley trains and extensive flats above features mapped as conventional river terraces marginal to the modern drainage net. Therefore direct run-off from a wasting glacier was not involved, though glacial ice may have persisted in the region. Major spreads of periglacial 'flood-gravels' were mapped in the Condover area (and confirmed by Crimes, 1985). Indeed, the western limits of the Norton Farm kame abut onto a flood-gravel surface which descends northwards to a gap in the Precambrian ridge. Kettle holes are not associated with the flood-gravels, suggesting that any melt-out that may have occurred had been completed prior to their final aggradation.

The glacial geological mapping of the Shrewsbury sheet was undertaken at a time when there was considerable interest in the concept of an ice-dammed lake in the lowlands. To an extent therefore, the fieldwork was a test of the lake hypothesis. This idea had been given coherence by Wills (1924), who argued that the Ironbridge Gorge of the River Severn was a glacial diversion of drainage initiated through overspill of a small, high-level, ice-dammed lake; with progressive glacial retreat, this became more extensive and of lower elevation as its outlet sill was lowered by the overflowing meltwater. He envisaged that the glacial lake stabilised for a time at an altitude of about 300 feet (90 m), and at this stage the feature was called Lake Lapworth. Subsequently, it lowered further and eventually drained, allowing the River Severn to establish its present day course. Accordingly, critical attention was paid to the nature of the landforms and sediments within the potential shoreline zone.

In the Shrewsbury memoir, Pocock *et al* (1938) were generally in favour of the glacial lake hypothesis; they postulated a number of small local lakes during the ice advance and retreat, and also subscribed to the Lake Lapworth reconstruction. In particular, the flood-gravels were interpreted as being graded to one or more glacial lakes. Having re-examined the terraces in the valley of the River Tern (Fig. 1) and east of Shrewsbury, Worsley (1975, 1976) concluded that there were field relationships, in the form of abruptly terminating glacial outwash terraces that were best explained as relict deltas aggraded into glacial lakes. At Shrewsbury, the eastern limit of the Shrewsbury Formation (till and outwash from the Welsh ice) lies near Fox Farm, 3 km northeast of Norton Farm Quarry, and this was interpreted as a former delta related to a lake at an altitude of 66 m. At Mousecroft Lane, the landform-sediment relationship shows that deformation of the Shrewsbury Formation post-dates its deposition, and originated in melt-out of residual glacial ice blocks buried within the underlying Stockport Formation. By analogy, it appears likely that the Condover kettle holes were also generated by melt-out processes after the Welsh ice advance event. At that time any residual glacial lakes would have drained via the developing River Severn drainage system to below the 65 m level.

The kettle hole with the mammoths

Although site of the mammoth find was interpreted as the fill of a former kettle hole (Coope & Lister, 1987), its morphological expression was subdued in

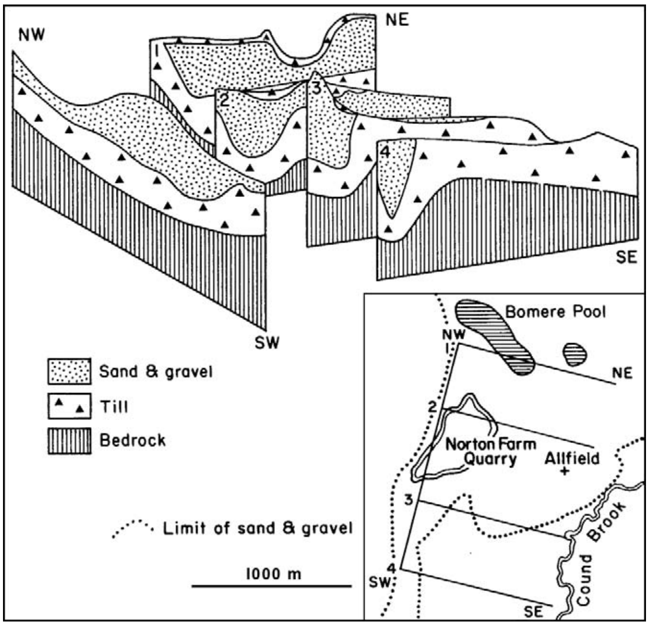

Figure 4. *Fence sections of the glacial sand and gravel and the till near Norton Farm Quarry, Condover; the mainly sub-surface extent of the sand and gravel unit lies within the dotted line on the inset map (adapted from Figure 11 in Crimes, 1985).*

comparison with many of the other kettle holes at Condover. The Liverpool geomophological map (Crimes 1985) did not show one at the find site. Fortunately, the original geomorphology can be examined on the Shropshire County Council air photographic survey of August 1983. These reveal an enclosed banana-shaped depression at the mammoth site. Comparison with the writer's field mapping (Fig. 3) shows that the northern end of this depression survives immediately beyond the margin of the quarry. The mammoth remains occurred midway along the axis of the depression which was around 300 m long.

Virtually all the recovered bone material was disturbed and had to be excavated from dumped overburden. Very few bones were found in situ. Nevertheless their stratigraphic status is not in doubt as the adhering matrix on the bones could be readily correlated with a specific bed in the surviving succession at outcrop. Seven units (**a-g**) were reported in the infill sequence that was about 10 m thick (Lister, 1993), and these are shown in the schematic section (Fig. 5). Field examination of the quarry in 1993 and 2005, showed that units a and b could still be identified in the north face adjacent to a lagoon on the quarry floor, with the remainder being obscured by vegetation and backfill. Beyond the quarry boundary in the field to the northeast, the continuation of the kettle feature could be identified; hence part of the infill succession survives as an important archive.

The first bed to accumulate in the kettle hole was the pink glacio-lacustrine clay (unit **a**) and this indicates standing water and an inflow with an abundant suspended load. The status of the following gravel (unit **b**) is less certain but might indicate collapse of the steep walls. Unit **c**, a dark grey silt about 1 m thick, lay in the middle of the infill; this is the key horizon, since it contained the mammoth bones together with pollen indicative of a treeless landscape dominated by grasses and sedges, the environment thought to be favoured by mammoths. This evidence, along with five radiocarbon assays on skeletal material giving a weighted mean uncalibrated age of about 12.5 ka BP, correlate with the first part of the Windermere Interstadial. Unit **d**, consisting of sedge peat, relates to the latter part of the same interstadial.

There then followed the final cold phase of the Last Glacial, the Loch Lomond stadial, when the grey clay of unit **e** was deposited. Nationally, this sub-stage was one of very active geomorphological processes; at Church Stretton, 15 km to the south, intense fluvial activity is recorded (Rowlands & Shotton 1971). In the immediate Condover area, no stratigraphic record outside the kettle fills is known, but it is possible that some deposition of the flood gravels occurred at this time. The humified peat and ploughsoil (units **f** and **g**) are both products of the Flandrian (postglacial).

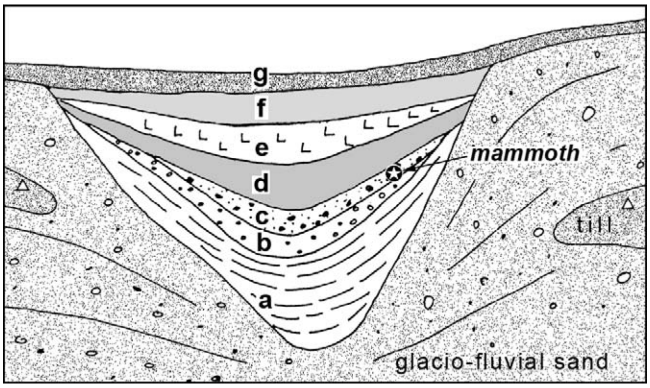

Figure 5. *Schematic profile through the kettle hole sediments; lithologies as in the text (after Lister 1993).*

The Condover mammoths

The preliminary report on the discovery of Mammuthus primigenius (Blumenbach) was by Coope and Lister (1987), along with a commentary from a North American perspective (Saunders, 1987). Subsequently, some details were amplified and modified as the analysis progressed (Lister, 1993; Lister & Bahn, 1995). About 400 disarticulated bone fragments were finally recovered from the dumped overburden debris. These represent the mainly complete bone kit of one adult male (without the skull, which was mysteriously missing; Fig. 6) and at least three youngsters - on the basis of three lower jaws. The adult male is estimated from size and wear of the lower teeth to have been close to 28 years of age, and the juveniles were between 3 and 6 years old. Since elephant siblings remain with their mother rather than their father, by analogy it appears likely that the mammoths at Condover were unrelated; this banishes romantic notions of a family group becoming stranded and perishing. The presence of fly and beetle fossils within the bone cavities, each signifying rotting fresh and dung, suggests that the carcasses were exposed for a period before sinking into the kettle fill.

Conclusion

At the maximum extent of glaciers during the Last Glacial Maximum, around 20,000 years ago, most of south Shropshire was covered by a major ice sheet. Initially this ice advanced from the north, and the generally red-brown colour of the Stockport Formation reflects the nature of the rocks over which the ice flowed. During the ice retreat a substantial thickness of till accumulated, along with outwash sands and gravels much of which was within ice-walled depositional sinks. Major blocks of glacial ice became buried in the outwash, and the overlying sedimentary cover retarded their wastage. In the Shrewsbury area, shortly after the loss of active northern ice, ice extending out of Wales (via the Upper

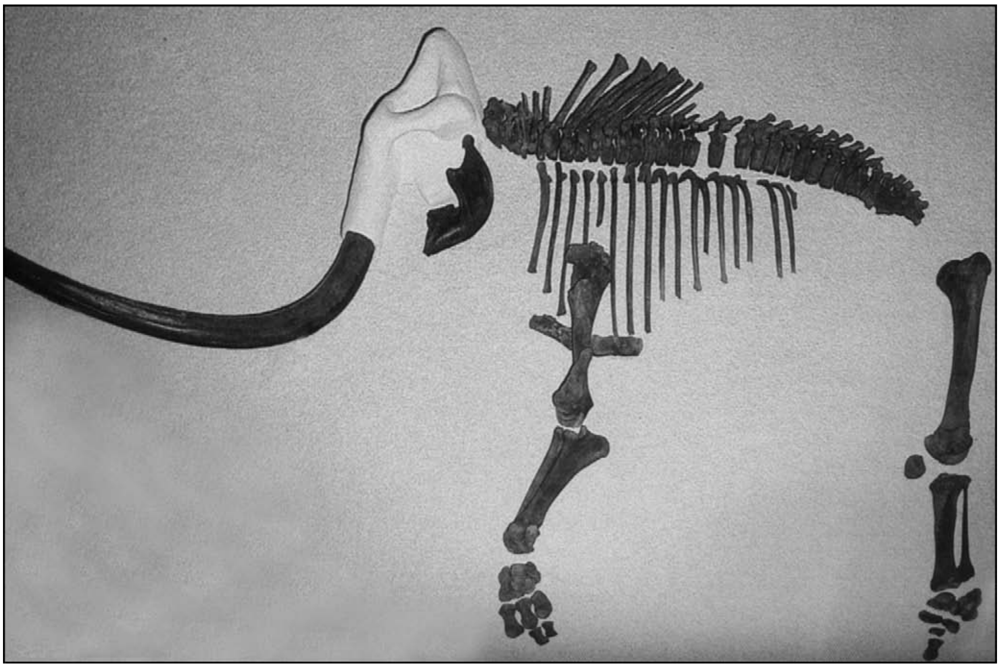

Figure 6. *The assembled left side skeleton of the adult mammoth; the white plaster represents the missing skull. The bones are now kept in the Ludlow Museum.*

Severn valley) deposited grey glacial till and outwash (Shrewsbury Formation) over the earlier till and outwash sediments.

Following Welsh ice retreat, the climate improved and the buried blocks of northern ice melted out to create the kettle holes and other ice-contact features that characterise the Condover landscape today. Concurrently sub-aerial drainage, some originating beyond the glaciated area, extended across the progressively draining lake basins. The flood-gravels mark the courses of these early periglacial rivers. Since these gravels are not pitted by kettle holes, it is surmised that the buried glacial ice had largely if not entirely disappeared before the flood gravels were deposited. Many of the kettle holes initially contained lakes, and these have subsequently become repositories of infill sequences containing records of environmental change, many of which extend through to the present day. Only the larger kettles have remained flooded until the present day, the remainder having been largely infilled and converted to swampy ground. At Norton Farm, one of these infills of late glacial age contained the remains of mammoths and it is possible that others remain to be discovered.

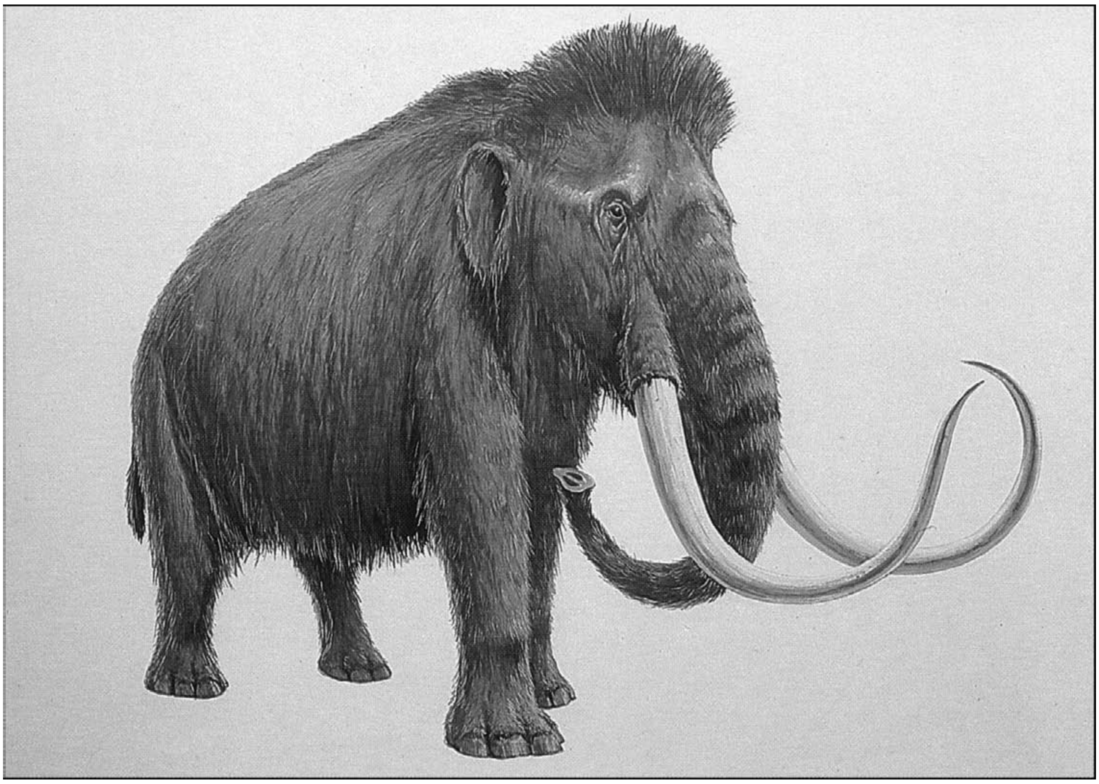

Figure 7. *Reconstruction of the adult mammoth. The original model is now at the Discovery Centre, in Craven Arms.*

Acknowledgements

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Building Stones of Nottingham

Albert Horton and Graham Lott

Abstract. The great variety of natural stone materials used on buildings in Nottingham, mainly as shop-front cladding, are described along two walks around the city centre.

Nottingham, like many other modern cities, has numerous buildings made of, decorated with, or faced in a great variety of natural stone materials. The stones used vary with the ages of the buildings, with locally sourced varieties dominating before the early part of the 19th century, and later a selection of stones from elsewhere in Britain. Today, Nottingham, like any other dynamic city centre, is characterised by architecture that uses stones from all over the world. Together these changes provide a splendid slice of urban geology that more than compensates for the almost complete lack of exposed bedrock. Nottingham also benefited from the distinctive design work of two local architects, Thomas C. Hine (1813-1899) and Watson Fothergill (1841-1928), whose buildings still dominate parts of the cityscape.

Historically the use of stone was limited by the feasibility and cost of transport. Early buildings reflected the materials that were available locally. Thus in the East Midlands, where good quality stone is not abundant, most structures were made of mud, or were timber-framed with infill panels of mud and straw; the use of stone was limited to the foundations and to major buildings such as cathedrals, castles and churches. After the late 18th century, the use of locally made bricks became dominant. The advent of canals and railways made a greater variety of materials available, when stone quarrying became an important industry throughout the 19th and early 20th centuries. But from 1920, the increasing labour cost (and extensive use of concrete) resulted in a steady decline in the number of working quarries. The use of stone is now very limited, and most commonly involves the repair, reconstruction or extension of historic buildings. Most new buildings are steel or concrete framed and possess only a thin cladding of natural stone (Fig. 1). Rising costs have resulted in the development and use of artificial stone, of which some types are good replicas (from a distance).

The variety of building stones within Nottingham may best be appreciated in two walks that loop around the city centre. Each walk will take around two hours. The stops shown on the route maps have been selected so that the walks display an optimum variety of the large number of rock types available in the city. Buildings are largely identified by their occupiers, but shops frequently change hands, so reference should be made to their sites, located and numbered on the map (Fig. 2). Change may also involve new facades within new corporate images, so readers should be aware that some stones (notably shop-front cladding materials) may have been changed since this text was prepared.

The stones most widely and repeatedly used are generally only described at their first sighting on each walk, unless improved examples are encountered later; notable among these are Portland Stone (limestone), York Stone (a trade name given to many Carboniferous sandstones and flagstones from the Pennines), larvikite and the Scottish granites. The Permian building stones from the Mansfield area vary from sandstones to sandy dolomites and limestones, so descriptions vary between individual sites. Many marbles are geologically limestones, as they are unmetamorphosed, but the term marble is used more widely in the construction trade to include any limestone that will take a polish.

__Figure 1.__ Cladding of sandstone, granite and larvikite, over the brickwork of the old Nottingham and Notts Bank (30), which was exposed during renovations in 2005.

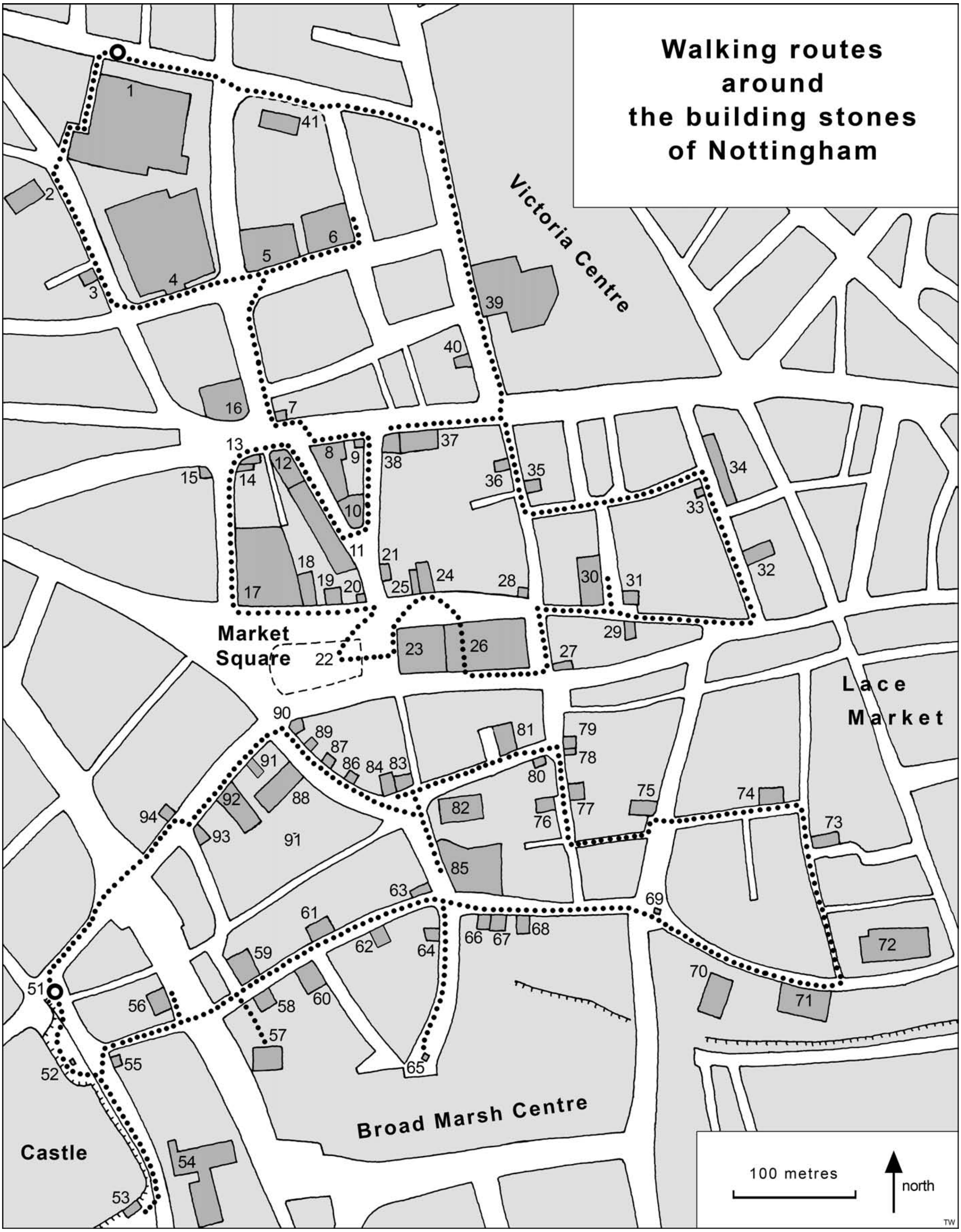

Figure 2. *Routes of the walks around central Nottingham.*

The northern walk

North of the Market Square

The walk starts at the Nottingham Trent University's **Arkwright Building** (**1**) in Shakespeare Street, a superb example of the decorative use and versatility of the Middle Jurassic Ancaster Stone from the Lincolnshire Limestone Formation (Fig. 3). This buff-coloured, well-sorted, shell-detrital, cross-bedded, oolitic limestone is laid as sawn (ashlar) blocks. Built in 1877-80 for the University College (before it moved to its Lenton site), the main door frontage is decorated with colonettes, statues, a frieze and decorative leaves. All are relatively unweathered, and illustrate the excellent freestone qualities of Ancaster Stone. The roof is covered with green Westmorland Slate. The boundary wall is a mixture, mostly of medium to fine-grained Carboniferous sandstone, with repairs of coarse quartz-sand artificial render; it also contains pillars, wall stones, and copings of Jurassic oolitic and shell-detrital limestone. Up Bilbie Walk, the eastern wall of the Arkwright Building has deteriorated due to weathering (near the steps of York Stone). After suffering major bomb damage in 1941, some of the original Ancaster Stone, with its characteristic wavy banding due to varying cementation, was replaced by fine grained sandstone; this was laid on edge, and now shows exfoliation (peeling) along the vertical bedding. Artificial sandy render has been used to repair some of the stones beneath the windows, but this has also blistered.

St Andrews Church (**2**) dates from the 1860s, and has been recently cleaned to reveal a delightful Victorian extravaganza. It is mainly built of variously buff, honey-brown and sometimes red-tinted Bulwell (Golden) Stone from the Permian Cadeby Formation (Lower Magnesian Limestone). This coarsely crystalline dolomitic limestone, dressed in pitch-faced blocks, was the most common building stone in Nottingham, almost always used in the stone boundary wall of properties dating from Victorian times onwards. Originally deposited as a limestone, it was subsequently dolomitized, and only traces of bedding remain; most of the detrital bioclasts and ooliths have been replaced by dolomite crystals, and small voids were left after the recrystallisation. There are up to eight decorative courses of thinly bedded, bluish-grey, silty limestone from the Jurassic basal Lias (formerly Hydraulic Limestone or Blue Lias, now Barnstone Member of the Scunthorpe Mudstone Formation). Ancaster Stone has been used as a low level plinth, an upper course, cappings to buttresses and in the mouldings of doors and windows. Unusually, the main entrance in Goldsmith Street is flanked by contrasting colonettes; to the left is a pink, medium-grained, dolomitic sandstone, possibly from the Permian at Mansfield, and to the right is a white, fine-grained oolite. The boundary wall of Bulwell Stone has a coping of Carboniferous sandstone.

Figure 3. *The magnificent Arkwright Building (1), with the Newton Building (4) beyond, both faced with limestones.*

Up Goldsmith Street, the former Indian restaurant (**3**)**,** between the brick-and-limestone Masonic Lodge and the old brick public house, has its front clad with a terrazzo - an artificial material of angular fragments of natural stone set in a synthetic cement; these fragments are dark grey marble from Italy.

Across the road, the Trent University **Newton Building** (**4**) is clad in white oolitic Portland Stone (Fig. 3). The larger sawn blocks of this Upper Jurassic limestone contain varying proportions of ooliths and shell-debris, mostly of medium to fine grain with banding, cross-stratification and scour structures that reflect current action at the time of deposition. Some blocks are richly fossiliferous with very large bivalves and rare gastropods, one block shows darker shell-debris-filled burrows. Differential weathering of the coping stones in the boundary wall has resulted in these harder fossil shells standing out from the matrix. By the main entrance in Burton Street, the most uphill block at street level of the protruding podium is a block of oncolitic limestone. Picked out by the weathering, the oncoliths are rounded, concentrically-laminated, algally-accreted grains of micrite (calcite mud), each up to 15 mm across. Some are broken and show signs of reworking. They are associated with stromatolitic masses, another shallow-marine, mud-binding, algal organism, which here show concentric banding with radiating fan-like structures. A layer of granite slabs that underframe the doorway are rapakivi granite from Finland (better seen at locality 25). Along the frontage, resistant Millstone Grit sandstone forms the lowest courses of the building; this prevents the damage, due to rising damp, that is seen in the Portland Stone blocks near the entrance.

The old **Guildhall** (**5**) bears witness to the freestone quality and durability of the Millstone Grit. The stone was quarried from the Ashover Grit at Sydnope, near Matlock. Built in 1887, almost entirely of sandstone ashlar blocks, and decorated with large columns, friezes and statues, the Guildhall shows little weathering except in the basal course, where rising damp and probably road salt splashing have caused some exfoliation. A hard, bluish-grey, fine-grained, thinly laminated, carbonaceous sandstone, probably from the Coal Measures, has been used in plinths, and in the steps and floor leading to the main entrance.

Next door, the ground floor of the **City Finance Department** (**6**) is clad with a medium-grey, poorly-cleaved, thinly-bedded slate sawn across its bedding. It shows extremely regular and parallel banding due to ultra-fine grain-size variation within the original, slightly silty, mudrock. This was subjected to low grade metamorphism, with the development of orientated mica crystals. The thin slabs have been sawn almost parallel to this poorly-defined cleavage at 60-70º to the bedding. Round the corner into North Church Street, the slabs are more brownish-grey; some of these show diffuse, brown concretions with compactional distortion of the outer lamination around large nuclei, within which the bedding traces have been destroyed. Black carbonaceous traces can be seen in places. This is probably the Silurian Burlington Slate from quarries near Ulverston, Cumbria. Panels around the main entrance in Burton Street were cut from a medium brown limestone, with pisoliths (concentrically layered grains) up to 6 mm diameter that are set in a darker brown shell debris-pelletal micrite (lime-mud) matrix containing possible burrow structures. Some blocks contain few pisoliths but many fossils. Original bedding is marked by rare clay partings. The whole is traversed by thin, slightly displaced, white calcite veins appear en-echelon in two directions, almost at right angles.

Across Burton Street, the large new Corner House block has columns of cast concrete faced to resemble a sandstone. On Upper Parliament Street, the **Turf Tavern** (**7**) was faced in 1927 with two types of green glazed ceramic tiles. Across the road, the old **Elite Cinema** building (**8**) is clad with white, glazed tiles known as Faience. It is decorated with glazed mouldings, shields and statues; these were made from a kaolin-rich clay that was fired twice, the second time with a salt glazing. Tiling became fashionable in late Victorian times because of its resistance to staining by the polluted air of the industrial cities. On the King Street corner, the windows of **Trent Bridge Travel** (**9**) overlie slabs of pale grey shattered marble with dark grey veins, which is the Devonian Grigio Fioritta Timau Marble from northern Italy.

Down King Street, the one-time **Prudential Assurance** building (**10**)**,** inside the corner to Queen Street, is built of red terracotta blocks with a glazed surface. Aggressive cleaning of the Peterhead Granite, on the half-basement and also in the two columns flanking the main doorway, has left most of it with a pale pink hue. The rock contains few mafic minerals, small xenoliths and veins of clear quartz, the crystal boundaries of which are clearly visible. The steps of red granite with large, pink, feldspar phenocrysts, are more typical of this rock. Across Queen Street, the old **Post Office Building** (**11**) is now a series of shops. It was built of Stancliffe-type Millstone Grit from Darley Dale, Matlock, and its large ashlar blocks consist of well-sorted, sandstone with scattered ferruginous grains. The pediment includes blocks of medium- to coarse-grained grey Rubislaw Granite, from Aberdeen, some of which has been replaced by a finer-grained grey granite. The original main entrance (now a display window of Milli's) is framed with blocks of the dark red variety of Shap Granite from the Lake District (see back cover). Up Queen Street, the new **Post Office** (**12**) is faced below its windows with a green, lustrous schist, with elongate flakes of mica that give the rock its shiny appearance. The sills were cut from green Honister Slate from the Lake District.

Back on Parliament Street, the ground floor of **O'Brien's** coffee house (**13**) has been clad with coarse equigranular Peterhead granite; small xenoliths (partially assimilated fragments of country rock, colloquially known as heathens) are finer-grained and darker due to the high proportion of mafic minerals. The stone is a mismatch with the brick-red, Scandinavian granite that was used when the side door in Market Street was realigned. Next door, a pale cream to brown Cornish granite has been used in **Graham Hill Menswear** (**14**)**,** but its paved entrance floor consists of varieties of red, purple and green phyllites, both riven and cut. Across the road, the **Reflex Bar** (**15**) has a frontage of Portland Stone on a plinth of rough-hewn, grey, Cornish granite. Across to the right, the columns and portico of the **Theatre Royal** (**16**) are painted, but records suggest that the columns and the capitals are of Ancaster Stone.

Further down Market Street, **Debenhams** (**17**) is a department store that expanded by incorporating lesser buildings. At its uphill end, yellowish-brown, fine-grained Monte Bracco quartzite tiles from the Italian Alps, north of Turin, floor the doorways. A dark grey gabbro is used beneath the windows, while mylonised grey Kemnay Granite from Aberdeenshire is used in the columns. The latter is medium-grained with a speckled appearance due to its white feldspars (with square cross-sections) and large brown feldspars (both are crushed), mica crystals and vitreous quartz. The rock is weakly foliated. Above the shop windows and the courses of white Portland Stone and then sandstone dressed to a vermiculation finish, the buff, rubble-faced wall is either a Carboniferous or Triassic sandstone (such as Hollington White); it contrasts with the Ancaster Stone of the window structures.

The Old Market Square

The traditional heart of Nottingham is an open-air geological museum, notably along the Long Row frontage with its colonnade of pillars of various rocks. The first ten, in front of **Debenhams** (**17**)**,** are square. Numbers 1 to 3 (starting from the Market Street corner) consist of dark grey to brown, coarse-grained, weakly foliated, Kemnay Granite with pale brown feldspars, dusky quartz, strings of mafic material including biotite, muscovite, and rare xenoliths. Pillars 4 to 6 are clad with pale greyish-cream granite containing flow-aligned, off-white feldspar phenocryst laths up to l0 mm long, from the De Lank quarries on Bodmin Moor, Cornwall. Pillars 7 to 10 reveal intensely deformed gneissose granite, probably from

Brazil, with deformed biotite mica schlieren (thin sheets), the whole cut by veins (Fig. 7); the parent granite underwent several stages of metamorphism. Panels below the shop windows appear to be a dark brown larvikite from Argentina. Intervening columns are clad in pale grey shelly limestone (biomicrite) consisting of coral (including Thamnopora), algal and bryozoan masses, and brachiopods, with the coarse shell debris set in a micrite matrix. The rock shows stylolites and micro-faults and is of Devonian age, possibly from Belgium.

In front of **Pizza Hut** (**18**)**,** round pillars 11 to 14 are made of grey, medium-grained Rubislaw Granite (Fig. 9); this has pale buff, zoned feldspar phenocrysts up to l0 mm long, with biotite and muscovite micas and rare xenoliths. Round pillars 15 to 17, in front of Vegas and the Lounge, are paler in colour with more quartz, but are weakly foliated and typical of the Kenmare granite from Ireland. The upper floors of the building are faced with white and pale green Doulton Carraraware ceramic tiles.

In front of **Schüh** (**19**)**,** and Clinton Cards pillars 18 to 22 consist of polished larvikite. This is a coarse-grained igneous rock related to syenite that comes from the Larvik area of Norway. About a third of the rock is augite, but most of it is made up of large feldspar crystals. These have a perthitic structure, as sodic feldspar exsolved from the plagioclase feldspar during crystallisation to create a micro-lamination within the crystal. Light reflected from these numerous internal surfaces produces the bluish iridescence known as schiller. Since the large feldspar crystals have diverse orientations, there is a play of colour as the surface is viewed from various angles. The effect is emphasised where the stone is cut and polished nearly parallel to the planar mineral fabric. Larvikite has been used extensively for external cladding of licensed premises, to the extent that it has become known as “publichouseite”, though its main use in England now is as armour stone to limit coastal erosion. Pillars 18 to 20 are the coarse, dark, Emerald Pearl larvikite, while pillars 21 and 22 are a finer-grained type, and the paler Blue Pearl larvikite forms panels beneath the windows of **Arden News** (**20**).

The wall panels behind pillars 18 and 20 consist of dark green and black brecciated and veined serpentinite. An unusual metamorphosed siltstone is used beneath the windows and as one course of paving at the Schüh shop (21); it has an uneven, weakly crenulated riven texture with a slight schistosity. The last three pillars, 23 to 25, as far as the corner at Arden News (20), each have 4 ribs and are compound in the lower part with grey Rubislaw Granite overlain by red Peterhead Granite. Behind pillars 23 and 24, columns around the windows of the Garage are a pale yellow marble with black minerals tracing lenticular metamorphic structures. The building above displays spectacular brick architecture by Watson Fothergill. Across King Street, superbly carved freestone of Millstone Grit sandstone (Fig. 4) is used in the window and door mouldings of the **Acton's** offices (**21**). Within the **Market Square** (**22**)**,** kerbstones along the pavement edging Long Row are of red granodiorite, probably from the Mountsorrel quarry in Leicestershire. In contrast, the other side of the road has kerbstones around the central paved area of pale grey granite, and the steps in the central open Square are the same material. Its large white feldspar crystals distinguish its source, but this could be any of various quarries within the complex porphyritic zones of the batholith that underlies Southwest England.

Dominating the square, the **Council House** (**23**) has a steel frame clad with thick slabs of Portland Stone. This well-known, white, Jurassic limestone from Dorset has varying proportions of ooliths, shell debris and intact shells, set in a crystalline cement of calcite spar, and some blocks show distinct banding of grains by size and composition. Its excellence as a freestone is illustrated by its wide use as the sawn ashlar blocks, and also in the fine carvings on the front of the building (Fig. 6). The coarse, porphyritic Cornish granite forms a plinth to the lion statues and also the front steps. The floor of the entrance patio has large square flags of York Stone quarried from the Lower Coal Measures Elland Flags near Halifax. These are enclosed by a grid of rectangular slabs of dark grey, micritic Carboniferous Limestone, which contain scattered crinoid ossicles, tabulate michelinid and rugose corals and cross-sectioned brachiopods.

Visitors may normally go into the entrance vestibule (but no further) and this is lined with a splendour of limestones and marbles. The walls consist of large panels of pale buff limestone with stromatoporoid masses and some rugose corals, the Cretaceous Perlato marble from Italy. The floor consists of pale cream, shelly, micritic limestones. Blocks of pale grey limestone with large cone-like rudist bivalves, probably from Iberia, are laid to form a circle, in the centre of which the City's heraldic arms has been created by inlay. This uses coloured marbles and limestones, pale and very dark green serpentinite, and small areas of brightly coloured stones, including lazurite. The back of the stag and antlers consist of an Upper Devonian Griotte marble from Belgium, while the yellow marble is probably from Siena in Italy.

In Long Row East, the **HSBC Bank** (**24**) has rough-dressed columns of pale grey, medium-grained, foliated Kemnay Granite that provide a visual contrast

Figure 4. *Delicate carving of sandstone on Acton's (21).*

with the same rock forming the polished columns in front of the adjacent **Going Places** (**25**)**.** The same granite, with xenoliths, is used as facing to the Bank. Columns between the windows of Going Places are reddish brown rapakivi granite from Southern Finland. Known as Baltic Brown, the rock is characterised by its golf-ball-size phenocrysts of orthoclase feldspar that contain small biotite crystals in roughly concentric bands. Many of the large phenocrysts also have a late-stage reaction rim of colourless or greenish-grey oligoclase feldspar, to produce the rapakivi texture (Fig. 15). The matrix has smoky quartz, mafic minerals and minor feldspar.

Exchange Arcade (**26**)**,** beneath the rear of the Council House, is clad with buff-coloured Bath Stone, a well-sorted Middle Jurassic oolite. In the floor beneath the dome, an inlaid compass is made of white Carrara marble from Italy and black Carboniferous limestone from the Pennines set into York Stone flags (Fig. 5). Through to Cheapside and left to High Street, **Barclays Bank** (**27**) has panels and its lower cladding of grey granite, probably from Sardinia, with its complexly intergrown and altered, pale fawn and white feldspars. On the corner of Clumber Street, **The Link** (**28**) has columns faced with slabs of green, fine-grained volcanic sediment. Metamorphosed to a low grade slate, this rock shows original grain-size banding, graded bedding and clay partings, but the bedding is now deformed. It originated as a water-lain tuff, and is quarried from the Ordovician Borrowdale Volcanic Group of the Lake District.

East of the Market Square

Up Pelham Street, **Tanners** (**29**) was built in 1860 as the Nottingham Journal Building. Its upper story facing is mainly brick with pale brown Millstone Grit sandstone quoins and window moulding. The same stone is used for a vine-leaf decorated frieze, with demons beneath the windows. Heads carved from sandstone stand at the base of the window arches. The first floor windows have narrow colonettes of pale pink granite. The ground floor fascia has been rebuilt and is now clad with a basal course of dark grey gabbro. This is succeeded by a narrow course of rapakivi granite (beneath window level), which is repeated higher up. The main panels are a pale greenish grey to fawn, folded and foliated migmatite with distinct crystal banding and swirl-like folded masses (Fig. 10). The source of this beautiful stone is unknown. Beneath it, the floor at the entrance consists of a terrazzo coarser than that seen at locality 3; it has inlays of various stones, including brown Sienna marble, pale-pink Italian Rosso Classico marble, grey Tranovaltos marble from Greece, green serpentinites, and the brick-red Ammonitico Rosso limestone that retains its pseudonodular sedimentary texture (Fig. 8).


Figure 5. *The inlaid compass in Exchange Arcade (26).*

In Thurland Street, the splendid building that originated as the Nottingham and Notts Bank is now occupied by **Prada** and another clothes shop (**30**). Built in 1877-82, this is often claimed as Nottingham's finest work by Watson Fothergill. The main structure is built of Darley Dale sandstone from the Millstone Grit, with the latest renovations using matching stone from Grindleford. An excellent freestone, this has been extensively carved to produce gargoyles, statues, and shields depicting the coats of arms of several Nottinghamshire towns; diagonal scoring was chiselled into the sawn faces, but some weathered blocks show cross-bedding. Red Permian Mansfield dolomitic sandstone was used for the colonettes, but some have been replaced with darker red sandstone, possibly the Triassic St Bees Red sandstone, which shows distinct bedding traces in several places. The pediment comprises grey Blue Pearl larvikite along the Pelham Street frontage and round the corner (Fig. 1). Further, along Thurland Street this is replaced by a medium-grey, medium-grained granite with distinct crystal banding, superb mafic xenoliths, quartz-rich pockets and thin veins; its gneissose texture suggests that it may come from Norway. To the right of the main door, a darker grey, finer-grained granite, perhaps from Rubislaw, has been used to complete the pediment across an original doorway. The succeeding course is Balmoral Red Granite that came from Finland with a trade name chosen purely for marketing; it contains both dark, mafic-rich and pale, feldspar-rich xenoliths. Some of the frontage has been replaced by blocks of a slightly darker and finer granite. A grey granite is also used in the colonettes beside the main entrance. Above the door, a carved medallion of medium-grained Mansfield Red sandstone is set in a block of buff, coarse-grained, micaceous sandstone carved to depict both Nottingham Castle and the Major Oak of Sherwood Forest. High above street level there are three exquisitely carved white Portland Stone friezes. The roof is covered with green slates probably from Cumbria. Visible from the east side of the street, a stone monkey stands against the brick chimney at the northern end of the building; a ‘monkey’ is a slang term for a mortgage and reflects the fact that at one stage the Bank owed money to the architect, who thus held a mortgage on the building.

Opposite is the **Thurland Hall** public house (**31**) which was built in 1906 using a Carboniferous sandstone, with decorative brick-red granite with red feldspar phenocrysts and also a white Carrara marble door step. A short way down George Street, an originally prestigious house (**32**) on the right is clad

Figure 6. *Portland Stone on the Council House (23).*

Figure 7. *Gneiss cladding in front of Debenham's (17).*

Figure 8. *Terrazzo floor in Tanners' entrance (29).*

Figure 9. *Gneiss and granite on Market Square (17-18).*

Figure 10. *Migmatite cladding on Tanners (29).*

with yellow brown ashlar blocks of Mansfield White Sandstone. Past the junction with Old Lenton Street, the former Watson Fothergill Architect's offices (**33**), were brick-built with typical decorative Millstone Grit sandstone dressings and carvings (Fig. 11). The building opposite, renovated as apartments (34), has basal courses of the fossiliferous and bioturbated, sandy, ferruginous limestone, that is Hornton Stone from the Lower Jurassic Marlstone near Banbury.

Through into Clumber Street, and within the new building, **Silver Screen** (**35**) has its central pillar and ground-level panels clad with a pale grey diorite; opposite and further up, **River Island** (**36**) has an unusual green gneiss forming the base of its columns; both stones are from unknown sources.

Round the corner in Upper Parliament Street, the **Express Chambers** (**37**) is another fine example of work by Watson Fothergill. The basal course near the Express Offices doorway is a grey sandstone, some blocks of which were face-bedded (laid with their bedding vertical) and now show severe exfoliation. The bulk of the building is built of the Carboniferous Ashover Grit from the Stanicliffe quarries at Darley Dale; it is a coarse-grained, honey-brown and buff sandstone showing traces of cross bedding. The red Mansfield Stone is used for alternate blocks in the window arches and in the ground-floor window colonettes and pillars. At the adjacent Express Buildings, now **Frankie & Benny's** (**38**), the same Watson Fothergill style has pink Peterhead and red granites in the door surrounds and under the windows.

On Milton Street, the main entrance to **John Lewis** (**39**) is clad with a pale, fawn, laminated, freshwater, micritic limestone, probably the Botticino Marble from Italy, with traces of ultra-fine shell debris and rare peloidal bands; it has distinct stylolites with some shallow channel structures. Across the road, **Pierre Victoire** (**40**) is faced with sandstone, red granites and two varieties of larvikite. The **Fire Station** (**41**) is built of a Millstone Grit sandstone, with doorways framed in grey, weakly-foliated, mica-rich granite. Continue past the significantly more attractive Arkwright Building, to the end of the northern walk.

Figure 11. *Architectural detail by Watson Fothergill (33).*

The southern walk

The Castle approaches

A castle has occupied the ridge of Triassic sandstone above the River Trent since the 11th century. After its Civil War demise, it was replaced by a grand mansion; this was then destroyed by fire and rebuilt in 1876-8 using pale-brown Coal Measures sandstone from the Trowell district. The walk starts at the Parish Boundary marker near the Castle Entrance at the top of Castle Hill (**51**). The wall is made of buff to brown, coarse dolomitic limestone (Bulwell Golden Stone) from the Permian (see locality 2); it is capped with York Stone sandstone from the Coal Measures. Paving setts below the marker are mostly from Charnwood Forest, including the distinctive greenish-pink Mountsorrel granodiorite and the granophyric diorite from the Markfeld quarry; some have zoned feldspar crystals, and there are also several bluish-white syenites and a basalt. The adjacent paving stones are York Stone flags, Carboniferous sandstones riven on their bedding planes. Across the cobbled roadway, paving slabs on the east side of Castle Hill are blocks of similar sandstone from the Namurian Rough Rock quarried at Scoutmoor in Lancashire; these have been sawn across their structure to show the concentric Liesegang rings that were created by oxidation on weathering fronts within its pore-water.

Below the castle approach, the bridge arch has a basal course of medium-grained Millstone Grit sandstone set into the Triassic sandstone bedrock. The arch is faced and lined by blocks of soft, pale grey, fine-grained sandstone with rounded quartz grains, which resembles the Triassic rock from near Castle Donington. Adjacent walls are built of this, mixed and capped with Bulwell Stone and Millstone Grit, and the surmounting tower was built more recently in ashlared sandstone. In the buttressed wall, the higher part shows honeycomb weathering of the sandstones.

The Robin Hood statue (**52**) rests on a plinth of a buff, pelletal, shell-fragmental limestone that is Clipsham Stone from the Jurassic Lincolnshire Limestone Formation. Its grains, up to 3 mm diameter, are oncoliths (algally accreted lime-mud particles) and pebbles of calcite mud (micrite). The wall behind the statue consists of coarse, rough-dressed sandstone, overlain by smooth sawn sandstone blocks. The panels of pale-buff to cream, coarse-grained, cross-bedded peloidal limestone are from the same Lincolnshire Limestone source.

Down the hill, Castle Road lies beside a cliff of Nottingham Castle Sandstone (Fig. 12), though much is lost behind masonry walling and an area of reinforced plastic coating (recently applied to curtail severe local weathering). The cliff was steepened prior to the building of houses (now removed) whose back rooms extended into the artificial caves that still remain behind the doors. The sandstone is weak, red-brown, medium-grained and cross-bedded, and was formed as a sequence of fluvial channel-fill deposits,

Figure 12. *Sandstone caves on Castle Road (53).*

with the base of each channel unit marked by a string of resistant pebbles, mainly of quartzite. The rock has been extensively excavated to create the many cave cellars in Nottingham, including the public bars at the rear of the nearby **Trip to Jerusalem** (**53**).

Wall panels below the windows of **People's College** (**54**) are clad in cleaved and broken slices of pale-greenish-grey, fine-grained tuff, with its grain-size and colour banding best seen near the main entrance. This volcaniclastic sediment was deposited in water, and was subsequently metamorphosed into a slate. It probably came from the Lake District quarries in the Ordovician Borrowdale Volcanic Group. Finer, dark grey, Welsh slate forms the window sills.

Up the eastern side of Castle Road lies the historic **Severns Building** (**55**). This 14th century house was moved from its original site on Middle Pavement; it uses no stone, but has a timber frame with an infill that was originally lime mortar and is now a granular cement. Through Castle Gate, **Castle Heights** (**56**) on Maid Marian Way has doorway panels of a brown, medium-grained syenite with fawn, fractured feldspars, and a weak lineation in elongated concentrations of mafic minerals; it is probably Fox Brown from Finland. An area above and right of the doorway has been clad in Portland Roach, an unusual type of Portland Stone; its cavernous texture results from the leaching of aragonite shells during diagenesis. The carved panel is typical, white, oolitic Portland Stone.

Figure 13. *Two limestones in St Nicholas's churchyard (57).*

The lower town centre

Across Maid Marian Way, **St Nicholas Church** (**57**), was brick-built in the 1670s with only the quoins and window mouldings of stone. The original quoins and parapets consist of White Mansfield, a pale-yellow, Permian, dolomitic limestone, with its characteristic green clay seams exposed in some of the lower blocks. A harder sandstone has been used to replace some of the limestone. Relative resistance to weathering is seen in some of the tombstones in the small church yard. There is a progressive reduction in durability from the hard Welsh slate (James Wardle, 1913, in the paving) and Swithland Slate (Abel Collins, 1705, against the wall) to the softer York Stone flags (Elizabeth Norton, 1791, in the paving) and Permian dolomite limestone (John Youle, 1811, against the wall), reflecting the changes in mineralogy and increases in porosity of the stones. Beside the path, a monument nearly 200 years old, to Mary Ann James and others, is also built of dolomitic limestone (Fig. 13). This has panels of a more durable, grey, fossiliferous, medium-grained limestone, extensively bioturbated and containing large bivalve and gastropod shells with serpulid tube clusters and rare corals; it is probably from the basal Jurassic Barnstone Member (formally the Blue Lias).

Castle Gate has a number of fine old town houses. Some have Carboniferous sandstone in the lower walls, window surrounds and porticos, while the **Trent FM** building (**58**) is of the Mansfield White dolomitic limestone. The ground floor of **Browne Jacobson** (**59**) has recently been re-faced with large blocks of pale, feldspathic sandstone, probably Darley Dale Sandstone from the Millstone Grit near Matlock. At the corner of Stanford Street, an office building (**60**) has a mixture of Carboniferous sandstone and Mansfield Red dolomitic sandstone used as a decorative course over the doors and windows; one sandstone block within the lower wall shows splendid Leisegang rings. Almost opposite, **Rodney House** (**61**) is clad with cleaved, green Westmoreland Slate, with black Welsh slate forming its window frames. The sandstone facing **Burdon's** solicitors' offices (**62**) contains small black flecks of plant detritus.

Before the corner with Lister Gate, a single broad column between the covered windows of **Wallis's** (**63**) is clad with a complexly foliated gneiss, probably derived from ultrabasic peridotite. This green rock is banded by variations in mineral composition. Many crystals are elongate and flecked with black specks of a mafic mineral, and mafic porphyroblasts developed during metamorphism along some layers.

Down Lister Gate, **Ravel** (**64**) has flanking pillars clad in Cornish De Lank granite. The unusual cladding beneath the windows and on a central pillar is a relatively hard, fawn, fine-grained, shell-detrital, oolitic limestone containing coarse bands of shell-debris, bioturbated in parts and with erosion surfaces; this may be Jura Kalk from the Middle Jurassic of Bavaria. In front of the Broad Marsh Centre, the statue plinth (**65**) is the dark, reddish-brown variety of Shap

Figure 14. Sandstone frontage on Galleries of Justice (71).

Figure 15. Rapakivi granite cladding Langford House (94).

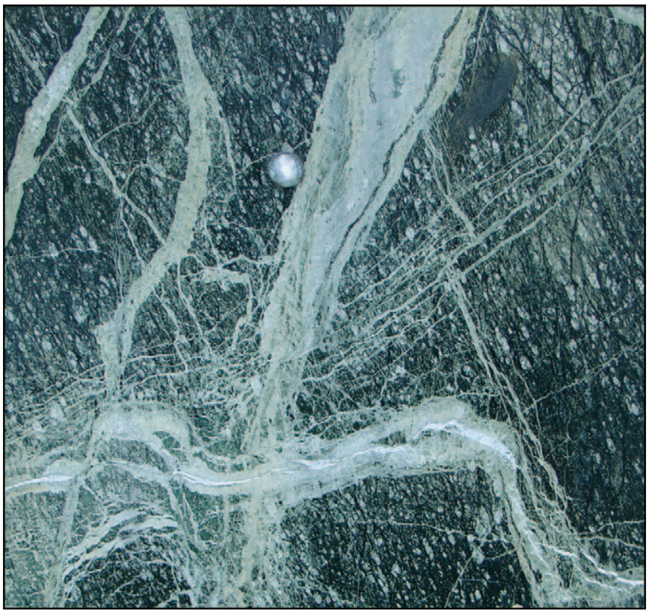

Figure 16. Serpentinite facing on the Orange Shop (86).

Figure 17. Travertine cladding on MacDonalds (83).

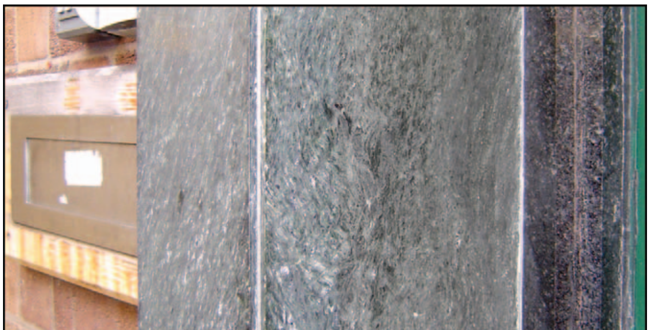

Figure 18. Phyllite cladding on Walkabout (92).

Granite, from the Lake District; it has large, pale-pink, euhedral, feldspar phenocrysts in a matrix of red feldspar, colourless quartz and black biotite mica.

Back on Low Pavement, the **Household Bank** (**66**) dates from 1920 when it was built as a house with Millstone Grit sandstone in ashlar blocks. The rock is a fawn, coarse, well-sorted, feldspathic sandstone with excellent cross-bedding. The adjacent, ornately decorated, Victorian Gothic town house built in 1876 (67) has Carboniferous sandstone courses, capitals, column bases, and oriole window surrounds. Its front columns are of dark grey syenite with white feldspars in a matrix rich in mafic minerals, possibly the Bessbrook Granite from Newry, Northern lreland; the columns by its door are cream-and-red-mottled, fine-grained, crinoidal limestone with many brick red veins, probably Devonian, and possibly the Ipplepen Stone from the Torquay area. Two buildings up the hill, **Enfield Chambers** (**68**) was built in 1910 of a dark-yellowish-brown, coarsely-bioclastic, oolitic, cross-bedded limestone. Damaged blocks show that the colour is a superficial effect of weathering, as the interior is buff in colour. The rock is almost certainly Middle Jurassic, probably Lincolnshire Limestone.

The Lace Market

At **Weekday Cross** (**69**)**,** the 1993 structure has a plinth composed of ripple-marked Carboniferous sandstone and a column of coarse artificial ‘sandstone’. Some of the surrounding area is paved with artificial stone, but there are also iron-stained York Stone paving flags, and these continue along High Pavement (Fig. 19). The nearby **Pitcher and Piano** (**70**) was formerly the Unitarian Chapel, erected in 1876 for the Anglo-Danish lace workers. It is built of cross-stratified Carboniferous sandstone with a pediment and string courses of buff, bioclastic limestone, a less iron-rich variety of the Lincolnshire limestone. Dating from 1770 as the County Hall, the **Galleries of Justice** (**71**) are built of a pale-green-grey, cross-bedded Triassic sandstone; this is distinguished by rare mud flakes (small flat pebbles of mudstone), and, in some blocks, small patches that are secondarily cemented. The frontage is high-lighted by four columns of fine-grained, pinkish-red, Permian, Mansfield Red sandstone (Fig. 14). Its left wing, once the County Gaol, is a Carboniferous sandstone that is slightly more pinkish in colour.

Figure 19. *Flagstone paving on High Pavement (69).*

St Mary's Church (**72**) is built of a diverse mixture of red, buff and pale-brown sandstones from the Millstone Grit. These are cross-bedded and contain scattered small pebbles of ironstone and rare, iron-rich, weakly-cemented concretions. Repaired sections are Bracken Hill Stone, a cream, fine-grained sandstone from the Carboniferous of the Pontefract area. Stone used in the North Chancel has a pimpled surface due to differential cementation and weathering. There is some fine decorative carving.

St Mary's Gate lies across the end of Broadway, one of the finest streets in the Lace Market, with its old lace factories and warehouses built of brick with sandstone detailing. On the corner, **NCN** (**73**) has below its corner windows pinkish and buff varieties of very-coarse-grained Millstone Grit. Round into Pilcher Gate, the offices of **Euro RSGG Riley** (**74**) are built of brick and Carboniferous sandstone; they are decorated with colonnettes of Scottish granite that are from Rubislaw beside the windows, and from Peterhead beside the door.

South of the Market Square

Across Fletcher Gate, **Cabaret** (**75**) is faced with tiles and mouldings of fired clay, and Byard Lane leads through to Bridlesmith Gate. **Flannels** (**76**) has a base-course facing and door plinth of rapakivi granite with its spheroidal feldspars; the doorway to the offices above has a surround of Portland Stone. Nearly opposite, **Jigsaw** and **Muji** share a building (**77**) with columns faced in dark diorite. The doorway to **Gala Casino** (**78**) has columns of pink Peterhead Granite on plinths of grey Cornish granite, with a pale, partially-resorbed xenolith exposed in the right front panel. Next door, **Berry's** (**79**) has columns faced in a pale marble with patchy texture.

In St. Peter's Gate, **Rutland Chambers** (**80**) has a doorway built of sawn blocks of brown sandstone with excellent current-bedding with colonnettes of Mansfield Red sandstone. Across the road, the basal courses of the old court building (**81**) are pale, red-tinted, buff, very coarse Millstone Grit sandstone, with its vermiculation dressing being destroyed by weathering. Above window-sill level, Ancaster Stone, a buff, fine-grained, oolitic limestone shows few bedding traces, but its wavy-banded differential cementation can be seen on the corner into Bank Place.

The upper end of the retaining wall to **St Peter's Church** (**82**) consists partly of coarse Millstone Grit sandstone. Downhill from the main entrance steps (of York Stone), the wall is of banded, shell-detrital, oolitic limestone from the Lincolnshire Limestone (either Clipsham or Ancaster Stone), above a basal stone course of, pale grey granite with milky white feldspar laths and colourless quartz. The oldest part of the church and the tower consist of large blocks of fawn Triassic sandstone. A similar sandstone, much less weathered, was used in the newer north aisle, but a variety of building stones has been used in the south aisle; a fine-grained Carboniferous sandstone is the most common component. There is a plinth and one course of very coarse shell-detrital, pelletal, oolitic limestone with bored intraclasts (pebbles of micritic limestone) and coral debris, and the buttresses are built of oolitic limestone; both these stones are probably from the Ancaster quarries in Lincolnshire.

Across the road, **MacDonalds** (**83**) uses the St. John's Travertine, from Tivoli, near Rome as cladding on its inner city branches (Fig. 17). The rock is banded calcite deposited by hot springs in an unstable environment where the centre of deposition was continually migrating, with consequent collapse and reworking of earlier sediment. This turbulent history is revealed in the ultra-fine lamination and banding, that is mostly planer but locally undulose, clearly seen in the polished slabs. Ill-defined pockets and bands of contemporaneous angular breccia fragments and of coated grains ranging from ooliths to pisoliths and larger oncoliths, are witness to current activity during deposition. The bedding is cut by vertical tubes which were infilled after the decay of the stems or roots of plants. Next door, **The Halifax** (**84**) is a fine example of ashlar construction using coarse-grained, shell-detrital, oolitic limestone, probably Clipsham Stone.

Down Albert Street, the fountain was carved from white marble, probably from the famous quarries at Carrara, in the Apuan Alps of northern Italy. Further down, **Marks and Spencers** (**85**) has a dark, greenish stone as cladding on the columns and lintels along the ground floor. This is Madre Perla, a cordierite gneiss quarried from lenses in the metamorphic belt of the Andes, north of Cordoba in Argentina. The panels are cut across the large, aligned cordierite crystals, which produce a pearly lustre akin to schiller in larvikite but in a totally different mineral. Panels beneath the windows are a dark grey gabbro, probably Bon Accord from the South Africa Bushveldt intrusion.

North up Wheeler Gate, the **Orange Shop** (**86**) frontage has been decorated with panels of coarse brick red granite with feldspar phenocrysts and colourless quartz, probably Balmoral Red from Finland. The main columns are clad with black and green serpentinite (Fig. 16). Originally a peridotite, this was sheared and metasomatised, possibly in several phases, to create a brecciated fabric with multiple shear zones; this deformation may have occurred during or after the serpentinization of the parent rock. **Nationwide (87)** has panels of dark grey Rustenberg Gabbro from South Africa beneath the windows. Panels of white crystalline metaquartzite adjacent to the door have irregular, ill-defined, grey, mafic-rich patches. **Virgin Megastore** (**88**) has columns clad in pink and white granite, standing on plinths of darker grey diorite, with panels of South African gabbro at pavement level.

Near the top of Wheeler Gate, **Herberts** (**89**) has columns of a grey, brown-stained, coarse-grained porphyritic granite, with white ill-defined fractured feldspars set in a feldspar-rich matrix including mafic minerals and small xenoliths. This Spanish granite has traces of foliation in the alignment of its two micas. The adjacent column by the doorway to the upstairs Federation Chambers has a contrasting cladding of Peterhead Granite, which is more acidic, with pink feldspars, colourless quartz, few mafic minerals and rare xenoliths. On the corner into the Market Square, the **Bradford and Bingley** (**90**) has two multi-faceted columns clad in dark medium-grained gabbro.

Across into Friar Lane, the isolated doorway into the offices of **BPP** (**91**) has its left side faced in an almost totally brecciated variety of serpentinite. This is darker and less altered than that used on the columns of Orange (86). Both varieties of serpentinite probably came from Italy.

Further up Friar Lane, **Walkabout** (**92**) now has a synthetic cladding except around the surviving old doorway at its far right end. This is framed with an unusual, greyish-green and brown, medium-grained, metamorphic rock with crenulated microfolds (Fig. 18). Stretching and breaking of the layers has resulted in concentrations of micas and quartz-feldspar groundmass. Originally a thinly-bedded, silty mudstone, the rock has been metamorphosed to phyllite; some panels show shearing and brecciation. **Harper Recruitment** (**93**), at the corner of Spaniel Row, is clad with dark grey gabbro. The main surface of each panel has been dressed to a rough, fractured surface, but this is enclosed in a smooth, cut and polished, marginal zone, which appears much darker.

Across the road, **Langford House** (**94**) displays the red, orbicular, rapakivi granite from Finland (see locality 25, and Fig. 15). The start of the southern walk is regained by continuing up Friar Lane to the Castle, and the beautiful rapakivi granite is a fitting stone to end the walking tours.

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Gang Vein and Gulf Fault, Wirksworth, Derbyshire

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Abstract. The E-W Gang Vein meets the NW-SE Gulf Fault at a 45° angle close to the crest of the Bole Hill anticline in the Carboniferous Limestone. Neither of these fractures appears to offset the other laterally, although many veins in the Peak District show evidence of wrench faulting. An analysis of the limited field evidence, together with old lead-mining records, including those of numerous branch veins, suggests that the Gang Vein was a normal fault at first, possibly a series of en echelon fractures, but later in post-mineralization times there is evidence of dextral wrench movement. Movements were episodic during the changing stress field from late Dinantian to Late Westphalian times. The Gulf Fault and its partner, the Rantor Fault, were normal faults, with their main movement in post-mineralization times.

During the author's study of the mineral vein pattern around Wirksworth, it has become evident that there are considerable uncertainties and differing opinions about the amount and direction of displacement of the two major fractures, the Gang Vein and the Gulf Fault. Neither their intersection nor their structural history has been studied. While field evidence is limited, old geological and mining records throw some light on the matter. It is the purpose of this note to draw attention to the problem.

Geological background

The Gang Vein and Gulf Fault cut the Carboniferous Limestone of the Bole Hill area between Wirksworth and Cromford at the southeastern corner of the Derbyshire limestone massif. The limestone is folded into the Bole Hill anticline with a roughly east-west axis and a gentle easterly plunge, diversified by a slight doming in the middle part of the Gang Vein. The overlying Millstone Grit Series is less strongly folded. The stratigraphic sequence has been described by Shirley (1959) and in the Geological Survey Memoirs and Reports (Frost & Smart, 1979; Smith et al., 1967; Cox & Harrison, 1980; Harrison & Adlam, 1985). Stratigraphic nomenclature was revised by Aitkenhead & Chisholm (1982). Walkden et al. (1981) and Oakman & Walkden (1982) described the cyclic nature of limestone sedimentation in the Wirksworth area. Gutteridge (2003) and Cossey et al. (2004) have added further detail concerning limestone facies and correlation. General geological guides were provided by Ford (1999, 2003).

The stratigraphic sequence is shown in Table 1. A total of some 350 m of limestones are exposed: their base is not seen. No geophysical or other evidence of the nature of the basement beneath the limestone is available. The limestone sequence has two toadstones (basalt lavas) intercalated. The Matlock Lower Lava, about 20 m thick, lies close to the Asbian/Brigantian boundary under most of the area, thinning out southwards. It overlies the Middleton Limestone Mine, but is not present in the Middlepeak Quarries. However, old mine plans and sections show it to be present beneath the Gulf and in the Rantor branch of Meerbrook Sough. The Matlock Upper Lava appears to die out before reaching the Bole Hill area (Walters & Ineson, 1981), though some allusions to a "Great Clay" in old lead mining records may signify either a thin Upper Lava or a thick wayboard. Several clay-wayboards (volcanic dust tuffs) are interbedded within both Bee Low and Monsal Dale Limestones (Walkden, 1972).

Descriptions of the mineral veins may be found in the Memoirs (Dunham, 1952, Dunham & Dines, 1946; Smith et al., 1967; Frost & Smart, 1979) and in Ford & Rieuwerts (2000). Details of the drainage soughs are in Rieuwerts (1987).

Gang Vein

This major mineral vein has an east-west course roughly along the crest of the Bole Hill anticline, though there is little exposure today. The early mining history was outlined by Kirkham (1953, 1963), though it is in need of revision in the light of recent archival discoveries, mostly by Jim Rieuwerts (*pers. comm.*). The outcrop of the Gang Vein lies in the rough ground north of Porter Lane, much obscured by grassed-over lead miners' waste hillocks. A length of some 1500 m can be determined from near Black Rocks in the east to the Gulf Fault in the west, with an extension beyond the latter to the west. The vein was worked from the

Namurian	Millstone Grit Series	Ashover Grit Edale Shales
Dinantian	Brigantian	Eyam Limestones Monsal Dale Limestones
	Asbian	Bee Low Limestones
	Holkerian	Woo Dale Limestones

Table 1. *Outline stratigraphy of the Wirksworth area.*

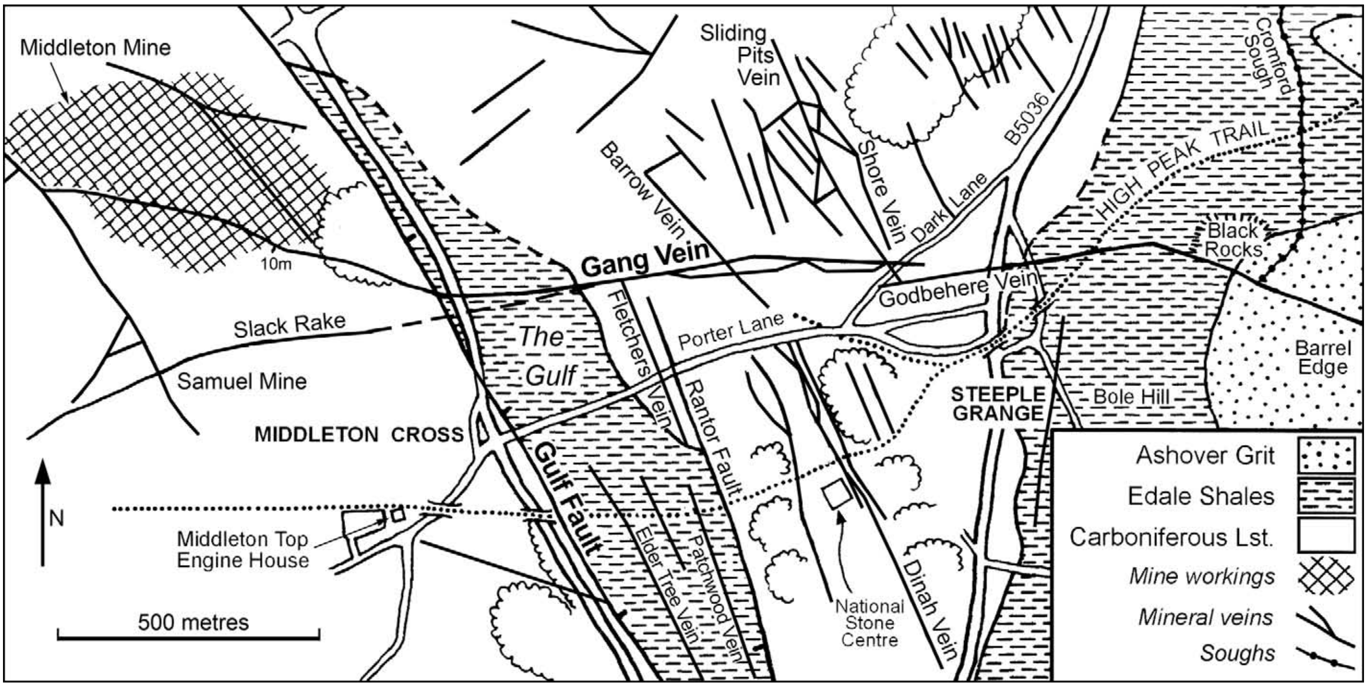

Figure 1. *Geological sketch map of the Middleton-by-Wirksworth area showing the Gang Vein and the Gulf and associated mineral veins (based on an earlier version in Ford, 2003).*

16th to the 19th century from about 24 named shafts at around 100-200 m intervals (Oakman, 1979), though early mining had many more (Rieuwerts, 1981 & *pers. comm.*). The named shafts are shown on mine maps compiled by Oakman (1979), Flindall (1974) and Rieuwerts (1980), and also on a series of 1:2500 maps compiled by the Barmaster (the principal lead mining officer), undated, but from around 1900-1910. In three places the vein splits over lengths of 200-300 m and lenses of limestone ("riders" in old mining jargon; Rieuwerts, 1998) up to 50 m wide lie between the two branches. It is possible that these splits represent en echelon faulting but without access or detailed mine plans it is impossible to be sure. There is also a dextral offset of about 30 m near Dark Lane shown on several old maps: this displaces the eastern end of the Gang Vein to the south and the part to the east is known as the Godbehere Vein, once worked from the Cromford Moor Mines close to Black Rocks. The offset is aligned with a NW-SE vein to the north – Sliding Pits, along which Vermuyden's Sough approached Gang Vein in 1651; Shore Vein is a northerly branch vein close by (Shaw in some mining records). Close to Black Rocks, Godbehere Vein curves somewhat to the southeast, and some maps show a fault splitting off almost due east, and downthrowing north at Barrel Edge, where the outcrop of the Ashover Grit is affected by landslipping. This fault does not appear on most old mine plans and its existence and nature remain uncertain.

Most of the Gang Vein was about 2-4 m wide, with galena, baryte and calcite as the main minerals and lesser quantities of sphalerite, pyrite and fluorspar. There was too little fluorspar to attract the modern spar miners and the area was judged by Dunham (1952) to lie outside the fluorspar mineralization zone, which may lie beneath the Edale Shales down the plunge to the east of Black Rocks and Barrel Edge.

Godbehere Vein was worked from the Old Engine Shaft (= Gin Pit) adjacent to Dark Lane to the most easterly "10th Meer Shaft", which is now run in, close to Black Rocks. The latter are generally regarded as a landslipped mass of Ashover Grit derived from Barrel Edge, though the crag may lie between two faults.

Gang Vein crosses the northern end of the Gulf (Fig. 1), but whether it is a fault cutting off the shale outcrop (Stephens, 1942) or not (Smith et al., 1967) is debatable, as the critical area is concealed beneath buildings and quarry waste. At least it can be said that the shales thin out to nothing before they reach Middleton-by-Wirksworth village. Most previous writers (e.g. Smith et al., 1967) have claimed that the Gang Vein was downfaulted to the north, but Carruthers & Strahan (1923) and Stephens (1942) argued that the throw was variable and in places was down to the south. Dunham & Dines (1945) also said the downthrow was to the south, though without stating the evidence. There have been few comments on either the amount of displacement or on the hade: some said that the hade was variable, north at the eastern end and south near the Gulf, though the evidence is far from clear. However, in a brief report on an exploration of one of the Cromford Moor Mine shafts on Godbehere Vein (close to the Black Rocks car park), Porter (1990) recorded that the shales were

30 m lower on the south side. His report included a photograph showing strong horizontal grooving along the walls of a stope. This clearly indicates horizontal movement, i.e. wrench faulting, at least after the emplacement of the mineral fill. Godbehere Vein was worked at a depth of some 150 m beneath the slope south of Black Rocks, where it was drained by Cromford Sough (driven between 1652 and c.1800, with several gaps; J.H. Rieuwerts, *pers. comm.*). Most of Cromford Sough was driven through shales and it intersected Godbehere Vein beneath the Barrel Edge escarpment of the Ashover Grit. At the intersection the north wall was limestone while the south was in shale. Deep beneath the dip-slope east of Barrel Edge, a branch of the later Meerbrook Sough drained workings about 30 m deeper around 1815. Internal pumping allowed workings to be taken nearly 50 m below the level of Meerbrook Sough. Other mining records indicate that when Cromford Sough was turned west along the "sole" (i.e. the lowest 17th -18th century workings), the miners took advantage of digging through shales along the south wall, confirming the southerly downthrow and demonstrating that the limestone dipped down the plunge of the Bole Hill anticline to the level of both Cromford and Meerbrook soughs beneath Barrel Edge.

Together the incomplete records show that the Gang/Godbehere Vein had a southerly downthrow of 30 m at least at its eastern end; it has a steep hade to the south at the eastern end (Porter, 1990). Its position close to the axis of a gently plunging anticline suggests that there was dextral wrench movement sufficient to place limestone against shale at the eastern end, perhaps over a length of more than 200 m. This displacement is not obvious on the surface outcrops, though roads and buildings obscure the position of the shale/limestone boundary: there may be an unexplained anomaly here. The post-mineral-emplacement wrench movement seen in Porter's (1990) photograph does not preclude normal faulting at an earlier phase, but no direct evidence is available.

Numerous mineral veins branch off both sides of the Gang Vein, the majority having a NW-SE trend. They are marked by lines of waste hillocks and there are few exposures, but most seem to be wrench faults with only minor displacement. There are also some NE-SW veins which may be tension gashes.

Across the northern end of the Gulf, old mine maps show Gang Vein splitting into WNW and WSW veins. According to Flindall (1982), the southerly branch, Jackson Grove, is aligned with Slack Rake to the west of the Gulf Fault (the Barmaster's map does not show an extension and Rieuwerts (*pers. comm.*) is also doubtful about the position of Slack Rake). However, a vein continues through Samuel Mine before curving somewhat to the southwest. Both the Geological Survey (Frost & Smart, 1979) and Flindall (1982) regarded this WSW branch as the continuation of the Gang Vein, the former indicated it as a minor fault downthrowing south. However, just inside the entrance to the Middleton Limestone Mine a WNW-ESE vein, sub-parallel to the entrance drive, has been regarded by the mine company as the Gang Vein. It is aligned with the northern (Gang Vein) branch across the Gulf. Regrettably there are no exposures of this critical section of either the Gang Vein or its WSW branch where they intersect the Gulf Fault, owing to quarry buildings and waste. Further into the limestone mine, the Gang Vein is a fault downthrowing 10 m to the south. Three other sub-parallel WNW-ESE faults have been intersected by the limestone mine: they have downthrows of 36, 21 and 30 m to the south. These faults all show patchy mineralization and localised old lead mine workings. One old mine level encountered recently (early 2005) lies along a fault which shows vertical slickensides at one point and horizontal slickensides at another, clearly showing two phases of movement (Paul Deakin, *pers. comm.*). The faults are difficult to relate to E-W and NW-SE veins on the surface and were not recognized there by the Geological Survey. The discrepancy may be due to some form of offsetting where the fractures pass through the lava.

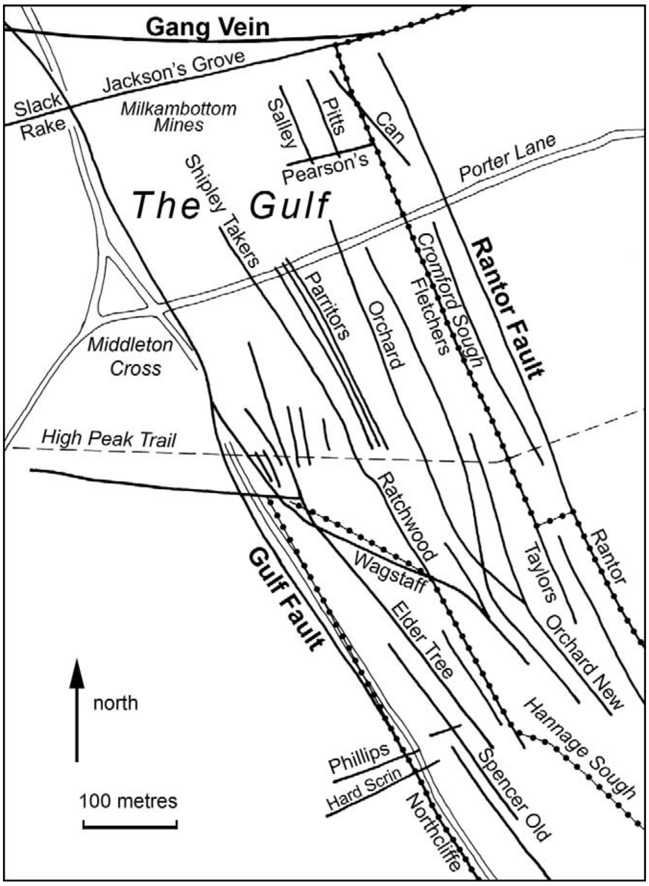

Figure 2. *Sketch map of mineral veins in the Gulf (based on a compilation by Flindall, 1982).*

The Gulf Fault

Bounded by the Gulf and Rantor Faults, the Gulf (Gulph in many old mining documents) forms a small graben with a NW-SE trend north of Wirksworth town. About 300 m wide it has several mineral veins along its length, parallel to the bounding faults: these may be step faults but no evidence is available. Southeast of the High Peak Trail (former mineral railway) the Gulf is floored by Edale Shales between the two limestone fault scarps, but the shales are entirely obscured by mine waste heaps. Much of the upfaulted western fault scarp has been quarried away in the Middlepeak and adjacent quarries. How far north of the Trail the shales extend is uncertain: their outcrop could "feather out" close to Middleton Cross or it could extend a few hundred metres further north – buildings and quarry waste obscure the area. .

The topographic contrast between the shale-floored Gulf and the up-faulted limestone masses led Shirley (1959) to regard it as a geologically young, post-mineralization structure, but in fact both the bounding faults are mineralized, the Northcliffe Vein following part of the Gulf Fault, and the Rantor Vein along the fault of the same name (Fig.2). The nature and throw of both faults is uncertain. Most geological reports give no amount for the downthrow on either fault, as no single stratigraphic horizon is visible on both sides. From estimates based on the probable position of the shale/limestone boundary on each side, the Gulf Fault has an average downthrow of around 150 m to the northeast. This is confirmed by Carruthers & Strahan's (1923) figure (quoted from Farey, 1811) of 486 feet (148 m) downthrow NE at Twentylands Mine towards the southern end of the Gulf. A section across the Gulf drawn by John Wheatcroft in 1831 also shows a downthrow of about 480 feet (146 m) measured between a "Great Clay" (= Lower Lava) occurring on both sides. It is uncertain how he determined this, as the Lower Lava is not present in Middlepeak Quarry west of the Gulf Fault; he did not show any Rantor Fault. Towards the southern end of the Gulf, at depth in Meerbrook Sough, the soughers' agent's reports indicate that the Gulf Fault was a shatter zone about 50 feet (15 m) wide with several fractures in a fault breccia of limestone, mineral matter, shale and water-worn limestone boulders (the latter suggest some form of karstic development, but no other data is available). Further north, near Middleton, the Matlock Lower Lava outcrops above the Middleton Limestone Mine entrance and is known in lead mines at depths of more than 100 m nearby, indicating a total throw of around 120-130 m down to the northeast.

In Via Gellia to the north of Middleton, the Gulf Fault seems to be dying out as it only displaces the Lower Lava by about 70 m down to the northeast. In Goodluck Mine in Via Gellia, the Gulf Fault was claimed to have been identified (Amner & Naylor, 1973), though the displacment was minimal and there was only minor mineralization.

The course of the Gulf Fault is along or close to the Wirksworth to Middleton road (B5023) - renewed movement might be a case of "tear along the dotted line". A small section of a fault plane, which may be either the Gulf Fault or a split off it, is visible at the road side near Middlepeak Quarry entrance: it dips steeply northeast towards the Gulf. A similar hade can be inferred from the fault's position along the road to where Twentylands Mine worked Northcliffe Vein, some 180 m east of the surface trace. At depth in Twentylands Mine the Gulf Fault was also found in Meerbrook Sough. Old plans show Northcliffe Vein as though it was nearly vertical, as is usual with most mineral veins, but clearly the fault has a distinct hade to the northeast, and this suggests normal faulting along the southwest side of the Gulf.

The workings of the Ratchwood Founder Mine (Warriner & Birkett, 1982) passed through the position of the Gulf Fault near Middlepeak Mine but only a simple nearly vertical fracture in the limestone was recorded by them. Several similarly vertical fractures in that mine mark the positions of veins within the Gulf. Otherwise no evidence is available of either normal or wrench directions of movement.

The Rantor Fault bounds the northeast side of the Gulf, with a displacement of around 50 m down to the southwest. The nearly vertical appearance of the fault

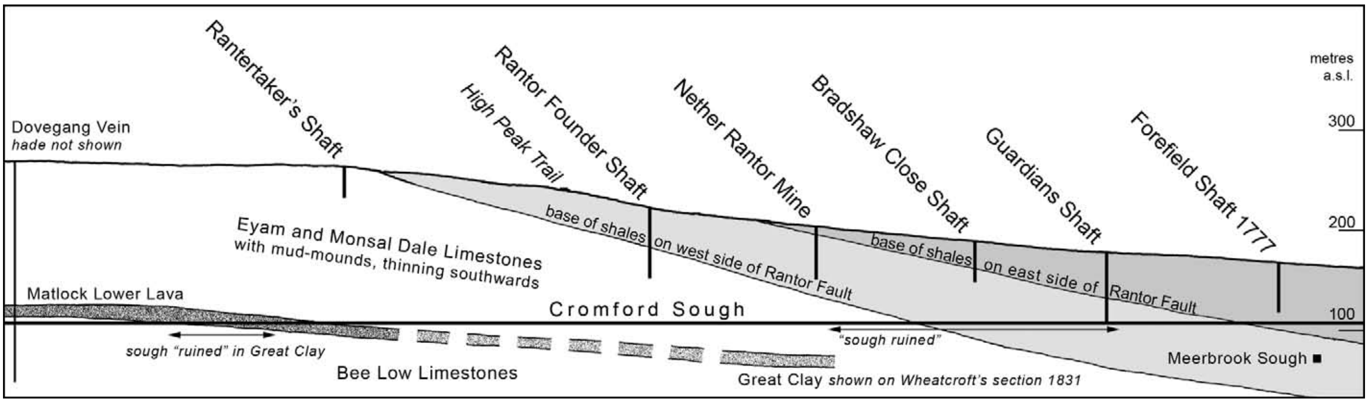

Figure 3. *Section along Cromford Sough, following the Fletcher and Rantor Veins (compiled by J. Rieuwerts).*

scarp at Raventor (= Rantor) and the presence of the Rantor Vein along it suggest that there is a dextral wrench sense of movement with the shale/limestone boundary displaced laterally. Rieuwerts (1980, 1981) has been able to construct a section along the Rantor Fault with the base of the Cawdor (=Eyam) Shales on each side (Fig. 3): this indicates that the downthrow may approach 100 m down to the southwest at the southern end of the Gulf. The branch of Cromford Sough driven southeast along the Rantor Fault was later "ruined" where it was in the shales. A branch of Meerbrook Sough driven northwest some 30 m beneath the latter also had problems in a "Great Clay (the Lower Lava). In the other direction, to the northwest of Middleton Cross, the Rantor Fault appears to die out leaving the Gulf structure as a half-graben. Still further northwest, the Rantor Fault was not recognized in Via Gellia.

The Gulf and Rantor Faults appear to be cut off by an eastern extension of the Yokecliffe Fault just south of Wirksworth; this has an east west trend with a downthrow to the south. Consequently, the Gulf structure cannot be recognized in the Millstone Grit country further south.

Discussion

The presence of horizontal slickensides on part of the Gang Vein and the lack of displacement where it crosses the Gulf Fault is anomalous at first sight, but in a vein dominated by calcite fill the horizontal movement required to produce horizontal slickensides may have been small. As noted above, one of the faults in the Middleton Limestone Mine shows evidence of both normal (vertical) and wrench (lateral) movement within a few metres. Also, if the Gang Vein is in fact a series of en echelon fractures, as its sinuous course and offset suggest, the lateral movement shown at its eastern end may not be present throughout the system. Quirk (1993) argued that the direction of the stress field changed through late Dinantian to late Westphalian times, and that the fracture/vein system was progressively developed in response to the changing stress pattern from late Dinantian times onwards. In the early phase (late Dinantian) there was no cover of Upper Carboniferous strata, so the depth of burial necessary for the mineralization process had not been attained. However, the limestones were lithified and could be subject to fracturing and folding. The early NE-SW extension in the stress field caused NW-SE fractures to open in the limestone up to the contemporary surface though there is little evidence of displacement. The growth of the Bole Hill anticline resulted in a major E-W fracture – the Gang Vein. Mineralization was later, as the process required a cover of 1500-2000 m of Millstone Grit and Coal Measures. Thus mineral emplacement mostly dated from late Westphalian times, when the hydrothermal mineralizing fluids utilized re-opened earlier fractures to form the vein system (Plant & Jones, 1989). Together these arguments demonstrate the polyphase nature of movement on the fracture/vein system. The sequence of events may therefore be as in Table 2.

Conclusions

From the limited field and underground evidence available, it is clear that there has been polyphase movement on most faults and veins from late Dinantian to late Westphalian times. The apparent anomaly of the intersection of the E-W Gang Vein with its wrench movement with the NW-SE Gulf Fault can be explained by the former being initially a normal fault system meeting the similarly normal Gulf Fault hading at an angle of about 45°. Later, post-mineralization wrench movement of the Gang Vein, shown by horizontal grooving in its Godbehere vein section, allowed it to cross the Gulf Fault without lateral displacement; its extension continued to the WNW through the Middleton Limestone Mine. Subparallel faults also occur in this mine. A WSW branch, Jackson Grove, also crosses the Gulf Fault and continues towards Samuel Mine.

1. Initial folding of the Bole Hill anticline was accompanied by NW-SE fracturing of the limestone surface in latest Dinantian times. The Gang Vein can be visualized either as a single east-west normal fault or possibly an en echelon series of faults, with a net downthrow to the south.

2. Deposition of the Millstone Grit and Coal Measures, gave a cover of 1500 – 2000 m of clastic sediments on top of the limestone. Burial to similar depths in adjacent basins gave rise to hydrothermal fluids which migrated into the limestone massif.

3. Renewed faulting with a NW-SE extensional stress field tended to give wrench movement on NW-SE fractures during late Westphalian times, but movement on the bounding faults of the Gulf was normal faulting, which did not give any lateral displacement of the Gang Vein, but resulted in Upper Carboniferous strata (Edale Shales) being down-faulted into the Gulf graben.

4. Mineralization in late Westphalian times resulted in the mineral suite being deposited in the re-opened faults.

5. Later, dextral, wrench movement, particularly on the Godbehere section of Gang Vein resulted in horizontally grooved walls of mineral fill and displacement of the shale/limestone boundary. The Gang Vein apparently crossed the Gulf Fault then without lateral displacement.

6. Enhanced folding of the Bole Hill anticline probably gave further wrench movement on many veins during the Variscan orogeny.

7. Erosion of the Upper Carboniferous cover occurred in post-Carboniferous to Pleistocene times.

Table 2. *Postulated sequence of tectonic events affecting the Gang Vein and Gulf Fault.*

Acknowledgments

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HOLIDAY GEOLOGY

Big Bend, Texas

Big Bend National Park and the almost adjacent Big Bend Ranch State Park are in the remote southwest of Texas. The two parks extend over 445 sq. km., forming the northeast extremity of the Chihuahuan Desert that covers much of northern Mexico. The southern boundary of the parks is formed by the Rio Grande, which is also the international border. For much of its length in the parks, the river follows the line of a fault with a 1500 m downthrow on the Texas side. This results in a 450 m cliff in the Santa Elena limestone that forms the back drop to many views.

Cretaceous limestone plus younger sediments and volcanics form the surface of much of the Park. The limestone has been intruded by Tertiary rhyolites. Block faulting and erosion of the limestone has resulted in rhyolite domes protruding through to produce the peaks of the Chisos Mountains. These dark red rocks contrast with the white limestone to produce a colourful landscape. Extrusive rhyolites and Tertiary basalts cap other mesas, and dykes form walls across the desert. There are many small canyons that show good sections through the lavas, tuffs, conglomerates and limestones.

At the National Park fossil exhibit, replicas of excavated Eocene mammal bones are displayed. The originals, plus various dinosaur remains that have been excavated, are in Austin. At the west entrance to the National Park, at Study Butte, there are the remains of cinnabar mining and mercury refining.

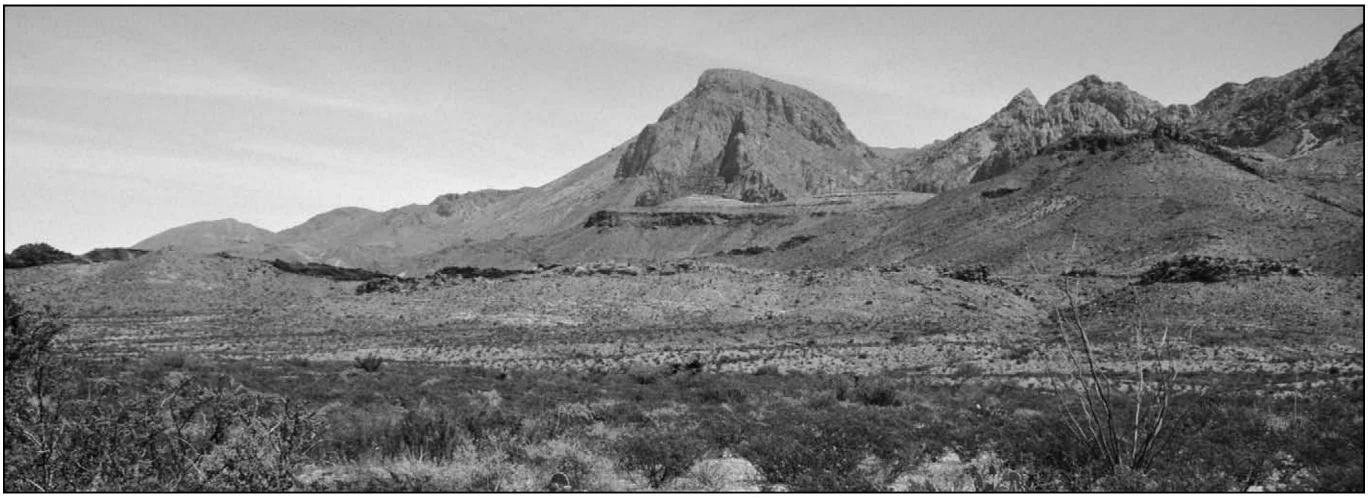
Around the north entrance to the National Park are older Palaeozoic rocks. These, and the Cretaceous rocks in this area, have been subject to multiple thrusting during the assembly of Pangaea and again on the opening of the Atlantic during one of the phases of Rocky Mountain uplift. The most visually striking of these steeply dipping rocks are the beds of gleaming white novaculite (a hard, siliceous rock formed by low-grade metamorphism of bedded chert). Subsequent continental relaxation, as part of the early Tertiary basin-and-range episode, produced the block faulting and allowed the igneous activity, the results of which can be seen today.

Both parks are visited by numerous birds and contain plants that are otherwise only found in Mexico and further south, so are of great interest to northern birders and botanists. The park emblem is the Road Runner. These birds are abundant and it is easy see why their comical demeanour inspired the carton character. They can reach a maximum speed of about 30 mph (when chased by a car); above this speed, they take off and glide into the scrub.

The temperature in April is around 30ºC with a pleasantly dry air and little likelihood of rain, though it is often windy. April is also the time that the desert blooms if there have been winter rains. The numerous species of cactus are decked with surprisingly large, yellow, red or magenta blooms while the ground between them can be covered with blue lupins and various species of yellow daisy. Bushes that have appeared to be dead for the rest of the year, burst into green leaf and colourful flower. There is an excellent botanical garden and interpretative centre near Lajitas in Big Bend Ranch State Park.

In spite of their remoteness, a survey by the National Parks Service shows that most visitors only spend one day in the parks. For anyone interested in geology and nature, a week would be time well spent.

Alan Filmer



In the Chisos range of Big Bend National Park, Ward Mountain is part of an Oligocene rhyolite dome that emerged through Eocene-Oligocene limestones and tuffs. The foreground of this view from Maxwell Drive is broken by the long ridges of the Chinese Walls that are erosion-resistant Neogene basaltic dykes.

HOLIDAY GEOLOGY

Pinnacles Desert, Australia

In the Nambung National Park of Western Australia, the Pinnacles Desert is noted for its spectacular karst landscape in the form of many thousands of limestone pinnacles. It lies 15 km south of Cervantes, a small coastal settlement 260 km north of Perth. The Pinnacles Desert is easily accessible by car along a circular track about 3 km long that provides many opportunities to stop and wander among these rare landforms. It is also possible to reconstruct something of the history of burial, karstification, reburial and re-exposure of the limestone pinnacles. As an additional stop in the area, modern stromatolites can be seen around the margins of Lake Thetis, a small saline lake a few kilometres inland of Cervantes near the turn-off to the Pinnacles Desert.

The pinnacles are the karsted remains of the late Pleistocene Tamala Limestone. This is up to 150m thick, though it has been locally reduced by karstic dissolution. The limestone is a calcarenite, composed of sand-sized grains of shells, algae and bryozoans, deposited in a near shore setting and as aeolian dunes (Lowry, 1974; Playford *et al*., 1976; Cockbain, 1990, McNamara 2002). Modern aeolian carbonate dunes along the coast towards Perth show how the Tamala Limestone was deposited.

The pinnacles are limestone pillars up to 3 m in height. They occur in elliptical groups several hundred metres across separated by areas of bare sand in which pinnacles are absent or scarce, and the groups generally, but not always, occur on topographic highs (Fig. 1). Individual pinnacles have three main shapes:

- Simple conical pinnacles with broad equant, sub-circular bases up to 1 m in diameter that taper upwards to a point. The lower parts of these pinnacles are greyish while the upper parts are brownish, with the colour change occurring at the same level within a group of pinnacles (Fig. 2).
- Composite pinnacles are similar in height to the conical pinnacles but have elongate bases up to several metres long, above which the composite pinnacles taper abruptly to one or two smaller slimmer terminations. The brown to grey colour change commonly coincides with the top of the broad lower part of the composite pinnacles.
- Split pinnacles are similar in size to the composite pinnacles, but are split by a vertical fissure that is infilled by calcrete (Fig. 3).

The pinnacles are formed of three materials. Most are made of well-lithified limestone. Some are formed of poorly cemented, cross-bedded calcarenite (Fig. 4); these are less common, perhaps because they are easily eroded. Many are coated by laminar calcrete and rhizocretions (Fig. 5).

Calcrete forms in semi-arid soils by the precipitation of calcite around roots and root mats often moulding themselves to any lithified surface within the soil, such as clasts or the bedrock. Some pinnacles have surfaces entirely of calcrete, but it is not possible to tell if this is a coating of calcrete or if these pinnacles are composed entirely of calcrete.

Outliers within the Pinnacles Desert show that the pinnacles were later buried by a succession of sandstone, probably also aeolian, with calcrete horizons interbedded with cross bedded calcarenite.

All these features point to a complex history of the pinnacles, starting with the deposition of the Tamala Limestone as aeolian carbonate dunes. These were cemented soon after deposition to form a lithified limestone; however, cementation was not complete, and some parts of the carbonate dunes were poorly lithified. The many closely spaced pinnacles formed when the bedrock underwent karstic dissolution, probably beneath a soil. Dissolution took place along vertical solution pipes, probably associated with the vertical root systems. In well-cemented limestone, the pinnacles represent pillars of lithified limestone left behind between the dissolution pipes. However, the formation of calcrete along fissures and within the

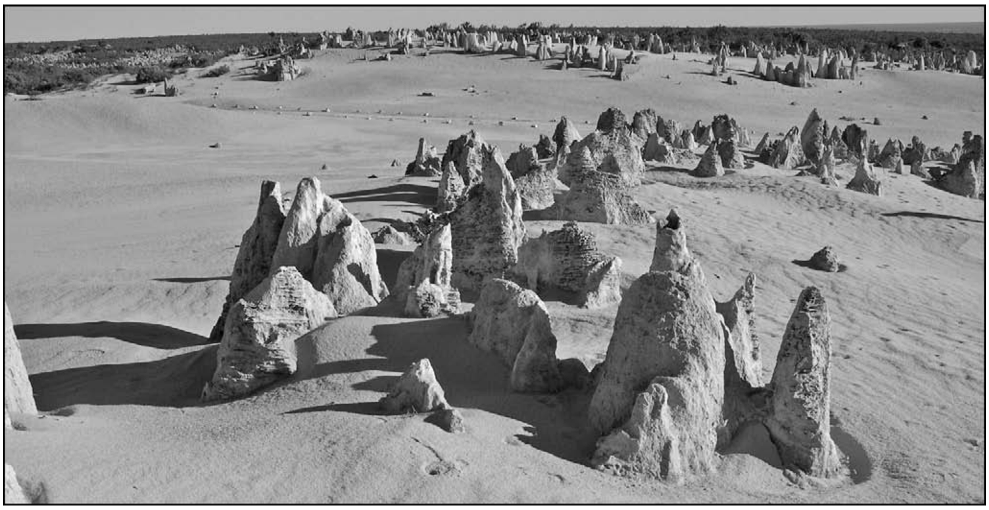


Figure 1. *Two groups of pinnacles located on topographic highs that are surrounded by areas of bare sand with few pinnacles. Topographic highs may correspond with buried aeolian ridges of the Tamala Limestone.*

Figure 2. *A group of simple and composite pinnacles made up of lithified limestone. The transition from the lower grey (light) onto the upper brown (dark) parts of the pinnacles takes place at about the same level within the group.*

limestone also contributes to lithification, known as case hardening (Jennings, 1985). Thus, in poorly lithified areas, the carbonate grains surrounding the solution pipes would have been eroded leaving pinnacles made of calcrete (e.g. Playford *et al*., 1976).

The presence of both karst and calcrete features, notably in the composite pinnacles, points to alternating periods of wet and arid climate during the development of the pinnacles. The broad bases of the composite pinnacles formed during the first episode of sub-soil karstic dissolution, and were then partly re-exposed and modified by a second phase of karstic dissolution; the brown to grey colour change may represent the level of exhumation. Split pinnacles are adjacent pinnacles that were 'welded' together by calcrete infilling their intervening fissure, and also imply a second phase of karstic dissolution. After this, the pinnacles were buried by aeolian quartz and carbonate sands - which have since been largely eroded, so that the Tamala Limestone with its karst pinnacles is exposed once again.

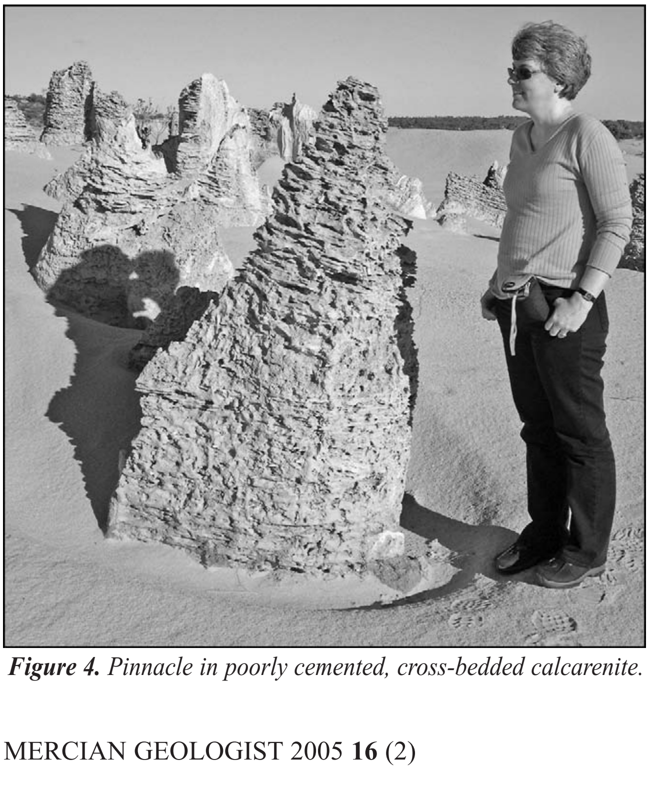


Figure 4. *Pinnacle in poorly cemented, cross-bedded calcarenite.*

Figure 3. *Split pinnacle (1 m across) cut by a vertical fissure filled by calcrete between two original pinnacles.*

When the Pinnacles Desert is seen from the air, groups of pinnacles appear to coincide with a number of sub-parallel sinuous ridges that cross the area. These ridges may represent the original crests of aeolian carbonate dunes in the Tamala Limestone that are now covered by vegetation. The distribution of pinnacles may thus reflect the original thickness variations of the limestone, with groups of pinnacles occurring over former dune ridges where it is thick, whereas pinnacles are absent between these ridges where the limestone is thin or absent.

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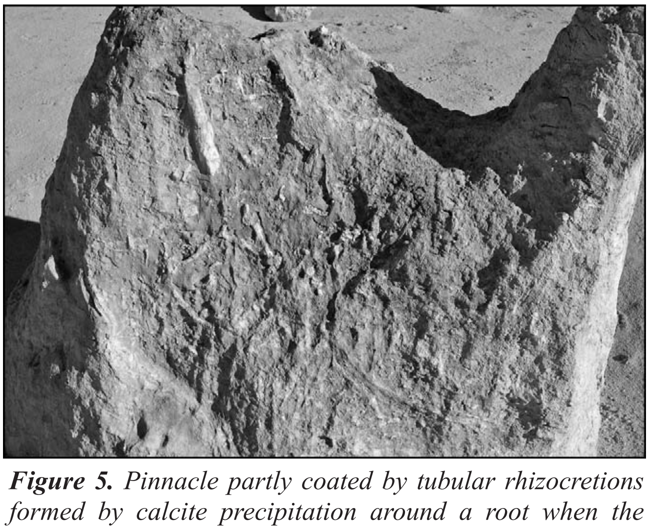


Figure 5. *Pinnacle partly coated by tubular rhizocretions formed by calcite precipitation around a root when the pinnacle was buried by soil. The pinnacle is 750 mm across.*

REPORT

Middle Jurassic Sequence at Ketton

At Ketton, in County Rutland, Castle Cement has one of the most extensive quarrying operations in the country. Lincolnshire Limestone (Inferior Oolite) and Upper Estuarine Clay (Rutland Formation) are worked to produce cement. A by-product is the Freestone oolitic limestone used as high quality building stone by the several local stone masonry operations.

Quarrying in recent years has revealed a nearly complete sequence of the limestones and clays of the Middle Jurassic across a small graben (Fig. 1). Exploratory work has reached the Upper Lias Clays, and Kellaways Sand (and possibly the Oxford Clay) are exposed at the top. All the intervening limestone and clay bands are present, except for the Lower Cornbrash. However, a rather battered specimen of the ammonite *Clydoniceras* was found at the base of the Upper Cornbrash (Abbotsbury Formation) and seems to have been reworked from the Lower Cornbrash before redeposition in the Upper Cornbrash.

An exploratory excavation in the middle of the quarry floor exposes the uppermost beds of the Lias Clay. Above this, Northamptonshire Sands Ironstone, once widely extracted to supply the steel industry at Corby, exhibits a boxwork structure resulting from spheroidal weathering. Poorly preserved bivalve shells are commonly found in the ironstone.

Immediately above the ironstone are the Lower Estuarine Beds (the Grantham Formation). These are fine sandy deposits, which vary considerably over a wide area. At Ketton, they are golden brown and almost as fine as dust. In other quarries, the same horizons are of a fine, white, silica sandstone that has been used for refractory products.

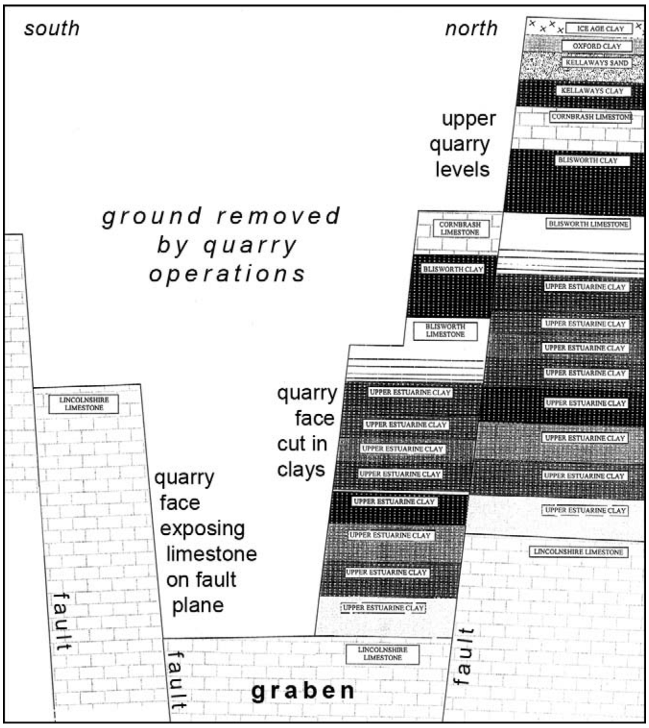


Figure 1. *Diagrammatic profile of the Jurassic succession exposed across the graben zone in Ketton Quarry.*

Figure 2. *Looking east along the line of the fault plane which forms the exposed face of Lincolnshire Limestone on the right. To the left, the downthrown Rutland Formation is capped by Blisworth Limestone, Blisworth Clay and Cornbrash. Where the main fault meets the skyline, the Cornbrash abuts the Blisworth Limestone to form an apparently continuous limestone band, though the fault can be traced from there across the floor of the upper quarry.*

Overlying the Grantham Formation, the lowest beds of the Lincolnshire Limestone are sandy, micaceous deposits cemented by calcium carbonate. In the nearby mines at Collyweston, one bed produces the Collyweston stone slates. These are riven along the bedding planes by exposure to winter frost, and the resulting thin "slates" form the picturesque roofs of the older buildings in the surrounding villages. These sandy limestones are not used in the manufacture of cement, and they form the floor of the main quarry.

The working face in the Lincolnshire Limestone is some distance from the excavation into the lower beds. The limestone grades upwards from a rather muddy rock to a nearly pure carbonate in the Oolitic Beds at the top (Fig. 2). The Oolitic Beds are believed to have formed as an off-shore, wave-agitated barrier with an extensive quiet lagoonal area on the landward side; they display no bedding planes and few fossils. The lagoonal beds show prominent horizontal bedding and vertical jointing, and are more fossiliferous. Bivalve shells and Nerinid gastropods are found. Rarely an ammonite is found - *Fissilobiceras* or *Sonninia*.

Above the limestones a disconformity represents the Bajocian uplift, when erosion removed an unknown quantity of bedrock from low-lying plains exposed for perhaps 5 Ma. Questionable features here include a karstic surface and some buried podsols.

The area then subsided at the start of the Bathonian. The lowest beds of the succeeding Rutland Formation (Upper Estuarine Series) are clays of freshwater origin that formed in an inland lake behind a coastal barrier. The bottom beds are highly siliceous and have been used in refractory products elsewhere. At the very base of the freshwater beds, an intermittent ironstone band is the horizon that yielded the remains of the dinosaur *Cetiosaurus* in a nearby quarry in 1968. This fossil may be seen in the Leicester New Walk Museum.

Above the freshwater beds lies a rhythmic sequence of some seven bands of differing colours. Each cycle begins with a densely shelly deposit at the bottom, which gradually gives way to vertical root beds at the top. These are then sharply truncated by the next shelly horizon. These probably formed in tidal mud flats (as around the Wash today), interrupted by periods of sea-floor subsidence.

The Blisworth Limestone (Great Oolite) lies above the Rutland Formation. This is highly fossiliferous, with many bivalves such as Pholodomya, Pleuromya and Modiolus. Ammonites are very rare but Nautilus is found. The echinoid *Clypeus* is common, as are gastropods and brachiopods. Occasional fish teeth occur and the humerus of a plesiosaur was found in the spoil from the Blisworth Limestone, though it is possible that this was an erratic. Above is the Blisworth Clay, green and purple and 4-5 m thick.

Next comes the Cornbrash (upper) known as the Abbotsbury Formation. Marked by a bed of abundant *Pleuromya* at the base, it is highly fossiliferous. The ammonite Macrocephalites is present, with many bivalves and brachiopods. The upper surface of the Cornbrash is paved with the giant clam *Lopha marshii.* Above the Cornbrash lie 6 m of the Kellaways beds, clay at the base and sandy above. Above these, there is a very small corner of clay, probably the base of the Peterborough Member of the Lower Oxford Clay. Ammonites are known from here, though the precise horizon of their origin is uncertain; seepage from the faulted limestone causes the clays to slump and become mixed (Fig. 3).

A cover of glacial till obscures all at field level. Probably Anglian, this yields Lias belemnites and *Gryphaea*, as well as chalk and flints, all exotics from North Lincolnshire or Yorkshire.

The main fractures are hinge faults striking roughly E-W to form a graben that dies out to the west (Fig. 4). Maximum observed throw is about 10 m, down to the north in two steps. The age and cause of the faults are uncertain. They may well be Pleistocene. The limestones lie above the Lias clays that are exposed in valley-sides, where loading pressure has caused widespread cambering, with valley bulging, noticed especially in the Welland valley when the pipeline was built to supply the Rutland Water reservoir. However, older tectonic faulting is also known in the area, specifically the Tinwell-Marholm fault.

The fault system and the whole exposure lie towards the limit of Castle Cement's quarry. When working ceases in this area, the operators are willing to create a RIGS, as it is the only place in the British Isles where the whole Middle Jurassic limestone and clay sequence can be seen in one quarry.

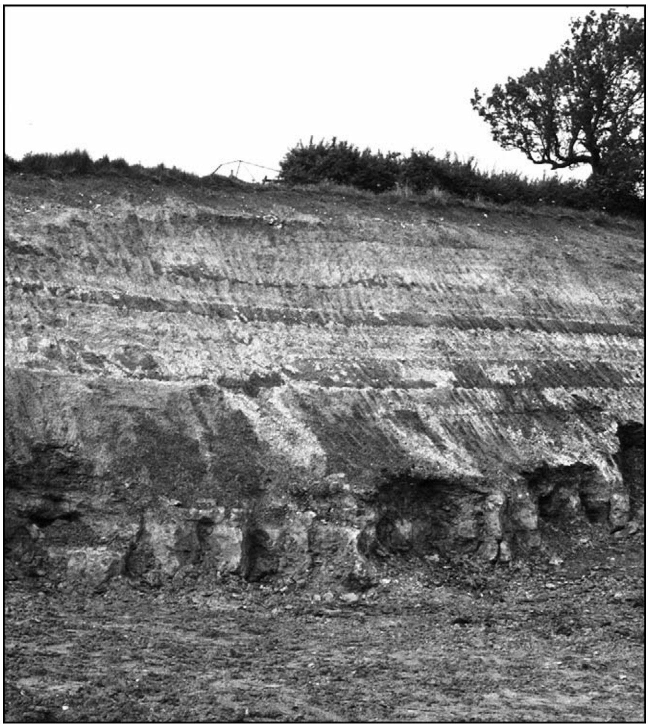


Figure 3. *A high level of the quarry with a floor of Blisworth Clay. Cornbrash limestone is exposed at the foot of the face, with Kellaways clays and sands above, and a cap of Oxford Clay probably survives just beneath the tree.*

Acknowledgement

Grateful thanks to David Bagshaw and Barry Bedford, Castle Cement's managers at the site for being so helpful in granting continuing access to their exposed geology.

Alan Dawn, Stamford Geological Society

Figure 4. *Looking west along the fault zone to where it dies out in the distance.*

EXCURSION

Old Cliffe Hill and Whitwick quarries Charnwood Forest

Leader: John Carney (British Geological Survey)
Saturday, September 18th, 2004

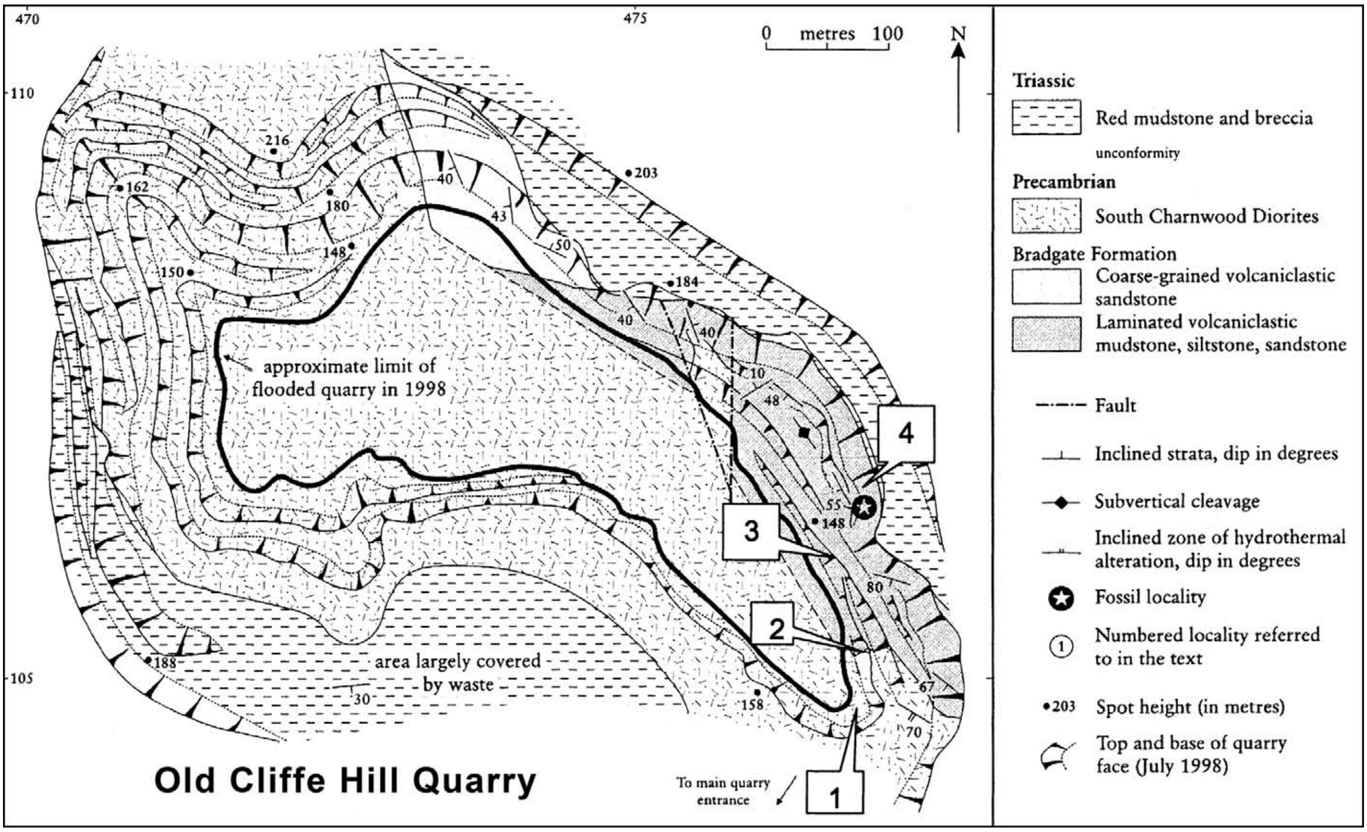
On a grey but fine Saturday morning the field party gathered at the offices of the New Cliffe Hill Quarry at the start of an excursion aimed at exploring two facets of Charnwood Forest's Precambrian geology. At the Old Cliffe Hill Quarry, rocks representing the very final intrusive stage of Precambrian magmatic activity are well displayed. By contrast, at Whitwick Quarry, a diverse assemblage of massive to fragmental igneous rocks is related to the earlier, extrusive phase of volcanic activity that was responsible for the accumulation of the volcano-sedimentary sequences forming the eastern outcrops of the Charnian Supergroup. Both quarries also offer sections through the highly irregular unconformity between Precambrian and Triassic rocks, and in particular they reveal the details of 'wadis', which are remnants of the Charnwood landscape as it existed about 240 million years ago. Safety regulations precluded the close examination of the higher quarry faces, but good examples of the range of lithologies abounded in the various piles of quarry waste, and were augmented by information obtained during previous visits by the excursion leader.

Old Cliffe Hill Quarry

After years of inactivity, this quarry (SK475106) was reopened in 2003 following the construction of a tunnel linking it with the main aggregate processing plant at New Cliffe Hill Quarry, 500 m to the west. This quarry is unique in that it clearly demonstrates relationships between volcaniclastic rocks of the Charnian Supergroup and a large intrusion of granophyric diorite. The intrusive rocks were named 'markfieldite' by Hatch (1909) after the quarried outcrops by Markfield village 1 km farther east, but in the Geological Survey Memoir (Worssam & Old, 1988) they are grouped within a unit called 'South Charnwood Diorites'. They are of great significance to regional Precambrian geology on account of their chemical and lithological similarities to an intrusion of granophyric diorite in Judkins Quarry at Nuneaton (Bridge *et al.*, 1998). A correlation between the two intrusions has yet to be conclusively demonstrated, but would imply that the minimum age of the Charnian Supergroup and its fossils is 603 Ma, which is the U/Pb radiometric age of the Nuneaton diorite (Tucker & Pharaoh, 1991).

At Locality 1, fallen blocks of the South Charnwood Diorites examined by the field party revealed a remarkably homogeneous rock with a grey, coarsely mottled appearance on fresh surfaces. The components forming these mottles include about 30% of dark green-grey mafic minerals (mainly augite and chloritic alteration products) and a similar amount of pale grey plagioclase feldspar crystals, either as aggregates or as rectangular euhedra. The remainder consists of pink to grey-green, very fine-grained granophyre, which in thin sections consists of radiating, graphic-textured intergrowths of quartz and K-feldspar. These rocks are less sheared and have considerably larger amounts of granophyre than a further set of intrusions, the North Charnwood Diorites, which are probably slightly older. Chemical analyses (Worssam & Old, 1988) suggest a range of compositions including granodiorite, quartz diorite and monzodiorite, with quartz monzodiorite the commonest variety. Locality 2 could not be examined on the day, but is important for showing that the contact between the South Charnwood Diorites and Charnian Supergroup volcaniclastic rocks is intrusive, rather than being everywhere faulted as some have supposed. Here, the diorite darkens and fines progressively in grain size within about 10 m of the contact, indicative of chilling. It then develops a very fine-grained porphyritic selvage (resembling a volcaniclastic rock), about 1.5 m thick, immediately adjacent to the host rocks (Carney & Pharaoh, 2000). The latter are recrystallised to a pale cream, fine-grained lithology over several centimetres from the intrusion, and here Boulter and Yates (1987) found evidence for contact-related 'metasomatism' in the occurrence of mm-size, grey-green 'thermal' spots. These are restricted to certain sedimentary laminae, and in places have been slightly deformed by the regional Charnian cleavage. Evidence for a Precambrian folding event, prior to diorite intrusion, is suggested in this quarry by variations in the stratal dip of the Charnian Supergroup along parts of the northern intrusive contact. Such relationships could suggest that the strata were folded, either before or during their intrusion by the diorite.

At Locality 3 the party examined a fascinating diversity of sedimentary rock types and structures in blocks that had become detached from the nearby quarry faces. The strata exposed in this quarry are tentatively correlated with the Bradgate Formation of the Maplewell Group, and here they mainly consist of green to grey, parallel-laminated volcaniclastic siltstones and mudstones. Today, the fine rain that had fallen helped to show up fine-scale sedimentary structures, which included normal grading, contorted lamination, slump-folding, rafted lamination and syn-sedimentary microfaulting. On previous visits, fallen blocks were found containing single beds with highly contorted lamination sandwiched between undeformed strata. These may be seismites - beds that preserve deformation caused by an earthquake event. The northern part of the quarry was not visited, but it chiefly exposes amalgamated beds of graded, crystal-rich volcaniclastic sandstone, each about 4-5 m thick. The strata in this quarry show no evidence for storm-



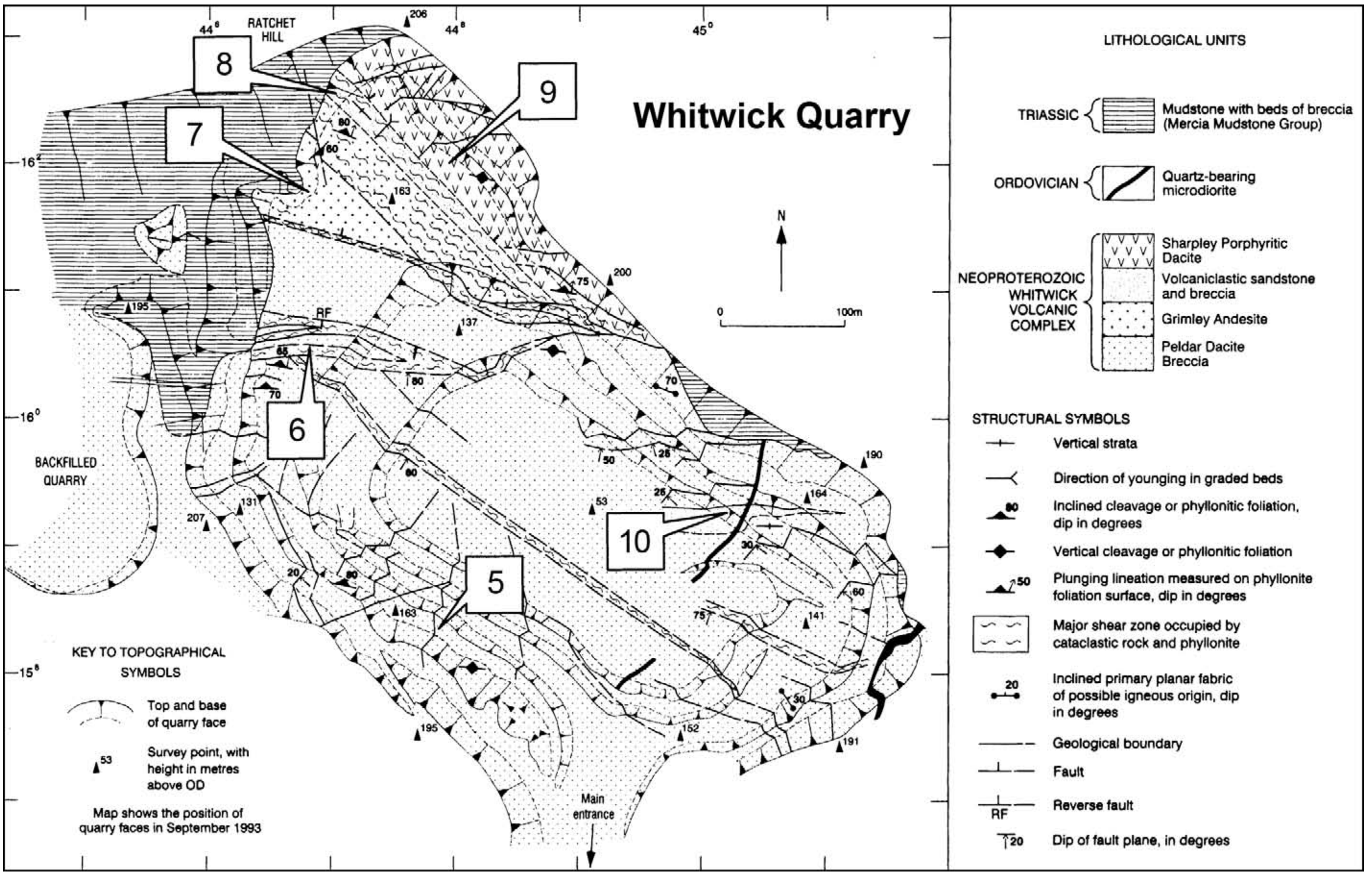
or wave-agitation and were therefore deposited at depths in excess of about 30 m. The common occurrence of normal grading indicates that the sedimentary particles were transported by flowage in turbidity currents, the overall environment being that of a deep marine basin marginal to a volcanic arc (Moseley & Ford, 1989; Carney, 1999).

Locality 4 contains one of Charnwood Forest's famous Precambrian fossil occurrences. It lies in part of the quarry conserved as an SSSI, but as this is situated on one of the higher and more inaccessible quarry faces it was not visited on the day. Here, a single bedding plane has yielded several discoid impressions, which Boynton (1978) first described and compared with the Precambrian fossil *Beltanella gilesi* Sprigg. Although the lack of internal detail raises doubts, Boynton & Ford (1995) later redefined these impressions and named one variety as *Cyclomedusa cliffi.* The other form recognised was *Cyclomedusa davidi*, which has no raised central boss.

Whitwick Quarry

The afternoon was taken up with a visit to this quarry (SK445158), which is currently disused. This is the type locality for the Whitwick Volcanic Complex (Carney, 2000), which consists of: *Peldar Dacite Breccia, Grimley Andesite* and *Sharpley Porphyritic Dacite,* all of these names following a nomenclature originally devised by Watts (1947).

The party first visited Locality 5, where blocks fallen from the quarry face showed details of a highly complex and little understood rock, the Peldar Dacite Breccia. Its most distinctive features are a dark grey to black appearance, abundance of large phenocrysts, and textures indicative of thorough brecciation (Carney, 2000). The rock is typically devoid of stratification, although other places in the quarry do show diffuse contacts between matrix-rich and matrix-poor breccia facies. This breccia is characterised by its numerous *porphyritic dacite fragments,* which vary in size from a few millimetres to over a metre. Although some are highly angular, many others have rounded to elliptical shapes, with incurved embayments and cuspate promontories reminiscent of pseudo-pillows. They have dark grey to black, fine-grained groundmasses enclosing large equant plagioclase phenocrysts and rounded phenocrysts of greenish grey quartz. The dacite groundmasses feature rounded, or rosette-like, microgranular clumps of strongly zoned quartz and feldspar. *Quartz microdiorite* fragments are medium-grained, pale green, and generally measure from a few millimetres to several centimetres in size (average about 50 mm). They are enclosed within both the breccia matrix and the porphyritic dacite fragments and commonly comprise a few per cent of the rock. In thin sections they mainly consist equant plagioclase crystals partly enclosed by quartz aggregates, the other constituents being interstitial albite, leucoxenized



oxide minerals, and chlorite-epidote alteration of original mafic minerals. The third component of this rock is the *matrix to the Peldar Dacite Breccia,* which is composed of crystal fragments and sliver-shaped volcanic grains, the latter possessing a fine-scale, spherulitic texture (Carney, 2000). Impressive specimens of the Peldar Dacite Breccia can also be examined in the walls of the nearby Mount St. Bernard Abbey (SK458163).

At Locality 6, the party examined parts of a major, bifurcating fault system that delimits the northern margin of the Peldar Dacite Breccia in the quarry. Individual zones of brecciated fault-rocks are tens of metres thick and some contain narrow, ductile shears in which the Peldar Dacite Breccia is recrystallised to a silvery-grey phyllonite – a type of fine-grained, foliated, tectonic rock mainly consisting of mica. In some ductile zones the foliation planes contain a faint mineral elongation lineation, which is defined by ellipsoidal areas of dark green-grey, chloritic material. The lineation invariably plunges down the foliation dip (northwards), and microfabric analysis (Carney, 1994) indicates that ductile movement was top-to-south, giving a reverse sense of throw for the fault complex. Argon isotope-series age dating of the micas (BGS, in progress) suggests that the ductile phase of fault movement was part of the Acadian (Siluro-Devonian) deformation event in southern Britain.

These fault zones were preferentially eroded in pre-Triassic times to form the wide palaeovalley, or 'wadi', intervening between localities 6 and 7 in the north-west of the quarry. Triassic red beds of the Mercia Mudstone Group subsequently filled the palaeovalley and here the party saw a fine example of a basal breccia composed of very local rock waste, perhaps a scree apron, derived from the valley sides. The breccia fragments are cemented by a matrix of pink, silty mudstone impregnated with veinlets and disseminations of calcite and possible barite. Beds of green-grey Triassic siltstone locally impregnated with malachite and with nodular masses of cuprite and tyrolite surrounding cores of native copper have also been found here (Carney *et al*., 2001). Such occurrences represent a classic 'unconformity-related' style of mineralization.

Grimley Andesite exposed at locality 7 is a grey-green, sparsely to moderately porphyritic, fine-grained lithology. Although appearing to be structureless, closer examination by the field party revealed that this rock has a shadowy breccia texture, similar to the Bardon Breccia seen farther south at Bardon Hill Quarry. The south-western margin of this exposure is strongly sheared over several metres, and has recrystallised to a silvery grey phyllonite. At Locality 8, the party saw that this margin of the Grimley Andesite is terminated by a subvertical screen, *c*. 30 m wide, of strongly sheared volcaniclastic rocks. In many places the sedimentary rocks have been converted to phyllonite with a foliation trending north-west, parallel to bedding and to the local strike of the Charnian cleavage. The original volcaniclastic rocks appear to have consisted of andesitic breccia, porphyritic dacite breccia of 'Peldar' type and fine-grained, laminated, volcaniclastic sandstone and siltstone. There are also thin volcanic breccias with fragments of Sharpley Porphyritic Dacite, which are interleaved between graded, crystal-rich volcaniclastic sandstones and purple or maroon siltstone. The opposite contact of these sedimentary rocks, with the Sharpley Porphyritic Dacite, is sharp. However, Within a centimetre, the dacite phenocrysts become smaller and more scattered, and small flames and rafts of purplish grey siltstone appear within the dacite.

At locality 9, the last of the day, impressive exposures of Sharpley Porphyritic Dacite were examined. The phenocryst assemblage is similar to that of the Peldar Dacite Breccia, but this rock is devoid of brecciation. Its fine-grained, microcrystalline groundmass is grey to lavender on fresh surfaces, becoming pale grey when weathered. Locality 10 was not visited, but is significant in that it exposes a large raft of sedimentary rock, enclosed within the Peldar Dacite Breccia. The raft is composed of volcaniclastic siltstone with highly contorted and slumped lamination. Its contact with the Peldar Dacite Breccia is a complex zone of mixing, with coarse-grained lenticles of the crystal-rich breccia matrix visible in the siltstone, and rafts and wisps of maroon siltstone incorporated into the adjacent dacite breccia matrix (Carney, 2000).

The exposures available in Whitwick Quarry, while impressive, are not sufficient to provide a full understanding of what these rocks represent. When the surrounding outcrops in this part of Charnwood Forest are taken into account, however, a model can be suggested that views the Whitwick Complex as a concentration of massive to brecciated andesites and dacites that represent feeder bodies, and possible subvolcanic domes, emplaced into the Charnian volcanic axis. (Carney, 2000). In this model the Peldar Dacite Breccia, with its pervasive fragmentation, is interpreted as a peperite, which is a mixed rock formed by the brecciation of a magma upon its injection into wet sediments. The Grimley Andesite is probably the root-zone of an extrusive volcanic dome, which upon collapse contributed andesitic debris identical to the blocks that make up some volcanic breccias in the surrounding Charnwood Lodge Volcanic Formation. The Sharpley Porphyritic Dacite is an obvious source for similar pale grey dacite blocks found in volcanic breccias seen in the nearby exposures on Ratchet Hill. It may therefore be a further example of a high-level intrusion, perhaps a sill or a cryptodome, emplaced within an unconsolidated to partly consolidated sedimentary carapace.

Acknowledgements

We are most grateful to the management and staff at Midland Quarry Products Ltd., for giving their permission to enter these quarries, and for their hospitality and assistance with arrangements both before and during this visit. This report is published with the permission of the Executive Director, British Geological Survey.

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EXCURSION

The apron reef above Castleton

Leaders: Gerard and Brenda Slavin

Sunday 11th July, 2004

Twenty three members of the Society met at Speedwell Cavern car park on a blustery but dry day, which was an improvement on weather in the previous week, which had left the hills sodden and slippery. Cars were used to shuttle to Peakshill Farm, from where a largely downhill walk could be enjoyed.

The aim of the excursion was to examine the northern apron reef which formed initially when the Asbian carbonate platform was an area of shallow water deposition and its northern edge was a footwall margin associated with the normal Edale Fault, downthrown to the north (Fig. 1). The abrupt shelf edge was at a high angle with depositional slopes of 20-30° into the Edale Gulf. During the Brigantian, gentler platform margins developed with the growth of extensive bioclastic sand shoals, but high relief was maintained by episodic movements on the fault. These shoals may be seen *in situ* in Pindale, Hope and Bradwell quarries (see a previous excursion, Gutteridge, 1996). Basinal accumulation of such bioclasts in submarine fans is seen in the "Beach Beds" near Speedwell Cavern. Coarser, post-Asbian "Boulder Beds" are seen at several sites around the northern margin, and these can be related to mid-Brigantian footwall uplift and subaerial exposure with karstification (Simpson & Broadhurst, 1968). Carbonate sedimentation ceased during the mid-Brigantian, following siliciclastic input from the north, and the carbonate platform was then on-lapped by the deep-marine Edale shales.

Around the Speedwell Cavern car park (NGR 138827), the Winnats cuts through the platform margin. The hill sides to both north and east are steep slopes of the exhumed Asbian platform margin. The cliffs within the gorge show the transition from shelf to shelf-margin and fore-reef. At the mouth of the gorge, and extending as far as Cow Low Nick, a series of coarse bioclastic beds on-laps the platform margin limestones. The crags behind the car park are now fenced off, but there are good exposures behind the Cavern shop. The bioclasts include rounded and smoothed brachiopods, sometimes with imbricate structure, and crinoidal fragments; graded bedding was debatably recognisable. Originally described as "Beach Beds", theses are now regarded as turbidites that originated from platform-top grainstone complexes, and are found more widely with intercalated shales in boreholes at Castleton and Edale (Sadler, 1964; Gutteridge, 1991, 2002).

Seen from the walk eastwards from the Peakshill Farm car park, the northern edge of the platform from Perryfoot to Windy Knoll is marked by a steep frontal slope with dips of 20-30°. At its base a line of swallow holes lies at the junction of limestone and on-lapping Edale Shales. Peaks Hill (118827) is a knoll of algal limestone bounded by crinoid-rich beds, which lies north of the main reef crest and separated from it by the valley containing Giant`s Hole. The party walked round the hill noting the variable dip directions attributed to differential uplift of apron reef deposits on the Edale Fault (Stevenson & Gaunt, 1971).

Giant`s Hole (119826) swallows a small stream into an open cave. With the help of a couple of ex-cavers in the party, its underground route was described, down a long vadose canyon and then through a deep phreatic loop to rise in Speedwell Cavern, before passing under the Peak Cavern gorge to rise again at Russet Well in Castleton (Ford, 1996).

Windy Knoll cave and quarry (126830) lie in the most northerly outcrop of the Asbian reef belt, which disappears here beneath the shales to reappear again in Treak Cliff. The roof of the cave is formed of a megatalus of pre-Namurian "Boulder Bed" lying on the Asbian limestones. In the main quarry face, tapering palaeokarstic fissures contain large limestone clasts in a dark bituminous matrix. The palaeokarst was sealed by Edale Shales, which also served as the hydrocarbon source. At the top of the face the deposit of limestone breccia with its rubbery elaterite matrix has been attributed to recent weathering following Devensian or later exposure (Gutteridge, 2002), and was examined with caution on slippery ground.

Passing the true top of the Winnats, a view point (135828) was reached. The origin of the Winnats Pass and gorge is debatable. It seems likely that there was no more than a shallow depression during deposition of the "Beach Beds" at the foot of the gorge, with further incision during pre-Namurian uplift associated with formation of the "Boulder Beds"; then after infilling with Edale Shales it remained buried, until exhumation by periglacial meltwater and runoff during the Pleistocene (Ford, 1987).

Above Old Tor mine (135827), good exposures revealed the Boulder Beds, with plentiful and photogenic Blue John crystals on the joint faces.

Treak Cliff (135830) has intermittently exposed algal limestone above a steeply dipping fore-reef slope that drops to the basin. Lunch was taken on spectacular colonies of branching corals originally identified as *Lithostrotion*, but now re-classified as *Siphonodendron*.

Prompted by sunshine, the party left the ridge and descended to a small crag on the fore reef slope (1343 8346) to see geopetal evidence that the observed slope of the fore-reef is original and is not tectonic (Broadhurst & Simpson, 1967). A walk northwards along the cliff top to join a path down the junction of the Edale Shales and the limestone to the Odin mine.

In the Odin fissure (134835) there was discussion on the movements of the fault, which shows not only horizontal slickensides but also vertical offset of the limestone-shale boundary across the fissure, implying some vertical slip (though this could be apparent due to horizontal displacement of the dipping beds).

An optional bolt-on to the excursion was a guided tour round Treak Cliff Cavern (136832) with Mr Peter Harrison. The cave gives a remarkable transect through the fore-reef and its overlying deposits. The entrance, dug through Edale Shale, leads into the cave, where initially shale forms the interstices of a post-Asbian "Boulder Bed" derived from the collapse of the carbonate platform margin, following subaerial exposure in the late Brigantian or early Namurian. The "Boulder Bed" is extensively mineralized by Blue John fluorite. The cave extends beyond the "Boulder Bed" into the fore-reef limestones, which dip steeply at 30-40° east but lack the fluorite deposition.

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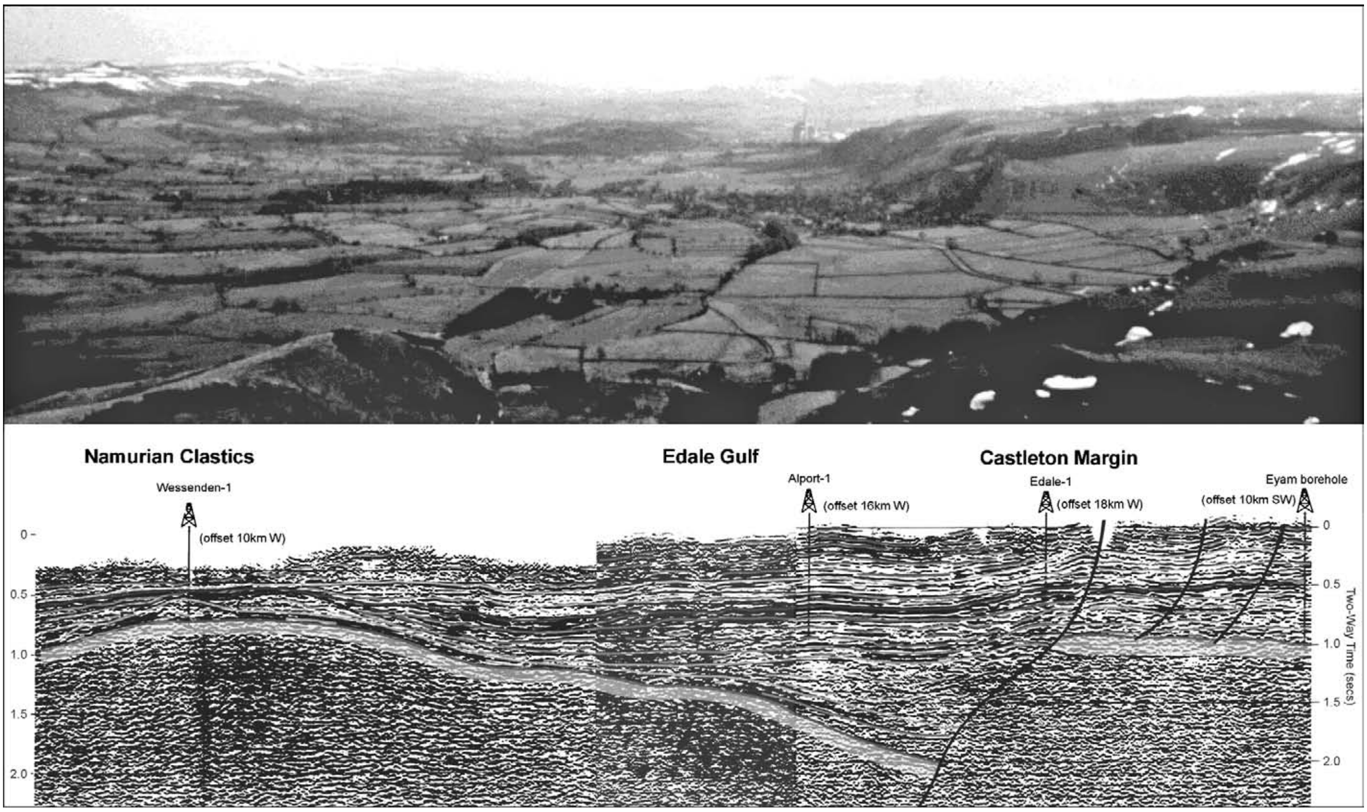


Figure 1. *Edale Fault, showing the Northern Edge of the Derbyshire Dome carbonate platform. Above: view looking east from Mam Tor; early Namurian shales in the valley onlap the now exhumed late Dinantian carbonate platform forming the valley side on the right. Below: the composite seismic line from the Edale Gulf illustrates the subsurface geology and highlights the half graben and fault-controlled geometry of the Dinantian basin; the top of the pre-Carboniferous basement is on the upper edge of the broad grey band that is 1 second down at each end of the profile. (From Fraser & Gawthorpe, 2003, with permission)*

Footnote: The leaders were somewhat embarrassed by the many pictures they had purloined from other authors` papers to illustrate their excursion handout, and in their defence pleaded the apologia of a Nobel Laureate of Literature:

"When `Omer smote `is bloomin lyre,
`E `eard men sing by land and sea,
And what `e thought `e might require
`E went and took -- the same as we.
Men knew `e stole: `e knew they knowed,
They never made no noise nor fuss,
But winked at `Omer down the road,
And `e winked back -- the same as us"

Rudyard Kipling

EXCURSION

Yorkshire Dales

Leader: Tony Waltham

Weekend July 31 - August 1, 2004

A return to the Yorkshire Dales seemed long overdue, and Ribblesdale was chosen as a venue to take in some of the classic sites and also a few places less well-known. Karst geomorphology on eastern Ingleborough and at Malham was interspersed with various localities at the limestone's basal unconformity and some fossiliferous sites at the top of the limestone. Members and guests numbered 24 for the occasion, and, after a cool start for the uphill walk on Saturday morning, the weather was delightfully warm and sunny. This allowed long rests on comfortable grassy fells, allegedly for geological discussion, during a long walk on the first day.

Limestone unconformity around Moughton

The party gathered on the Saturday at the Helwith Bridge Inn, and then took the cars to convenient parking below the Foredale Cottages (NGR 802701). Directly up from the cottages, the old Combs Quarry (800702) provides a spectacular exposure of the basal unconformity of the Carboniferous Limestone overlying steeply dipping, flaggy, laminated siltstones of the Silurian Horton Formation (Fig 1). The leader described the unconformity at the northern end of the exposure as having clean limestone in contact with the basement, with no basal conglomerate, and with about 1 m of relief on the unconformity suggesting marine invasion of a rocky foreshore (the close-up view is not worth the climb to it). It was the first of four localities that revealed environmental variations within the Carboniferous marine transgression.

Higher up, Foredale Quarry (800705) was worked in the limestone until about 1940. About 6 m of the thinly bedded, dark grey, muddy limestones of the Kilnsey Formation are only exposed at the quarry's southern end, while the upper 5-10 m of the quarry worked the Cove Limestone of the overlying Malham Formation. One face exposure was recognised as the wall of a meandering canyon cave that had been breached by the quarry working. It exposes stylolites in the limestone, developed in response to crystal orientations during pressure solution across a bedding plane or shale parting.

A break in the uphill walk onto the Moughton benches (790720) took in the view east. There was some discussion as to whether Pen-y-ghent Hill constituted a crag protecting a tail (in glacial style) extending south to and beyond Overdale (833708); the tail has a limestone core, but a till element on it was recognised by the softer drift topography. The leader suggested that a basement rise occupied almost the same position, as streams off Fountains Fell sink underground, where cave drainage is deflected away from the lower Ribble valley, as it all emerges at Brants Gill Head (812730) near Horton; whether this is due to folding of the limestone or to a buried basement ridge awaits detailed mapping.

A stroll across Moughton offered panoramic views from Ingleborough to Penyghent. The party looked down onto the Moughton Whetstone Spring, but did not descend to the poor outcrops of the Silurian whetstone siltstones where red and green banding may be due to weathering of Carboniferous age just beneath the limestone unconformity. On the plateau top, limestone pavements may be of poor quality due to by-gone, patchy removal of the top bed (with its better rundkarren forms) for rockery stone. The beds were viewed northwards into a shallow syncline that had been excavated into a stratimorphic depression (786726) by ice scouring weaker limestone cap-rocks as it overflowed from the Ribblesdale iceway into Crummack Dale. From Beggar's Stile, the party turned south, into the dale.

The basal unconformity was seen again at Austwick Beck Head (776718), a powerful rising of all the water sinking in the potholes of the Allotment, 2 km to the northwest. The flooded cave passage is on a bedding plane rising on the gentle dip about a metre above the unconformity. On its northern bank, the basal limestone has very few pebbles and lies over Ordovician mudstones that appear to exhibit Carboniferous weathering in the top few metres below the unconformity. In contrast, the southern bank exposes a basal bed more than a metre thick with well-rounded pebbles and cobbles of Ordovician mudstone within a limestone matrix. An almost-level bedding in the basement mudstones was observed to reveal a lozenge-pattern of jointing (Fig. 2); this was considered to resemble boudinage that could be ascribed to tension during strong Caledonian deformation of the region.

***Figure 1**. The basal unconformity in Combs Quarry.*

Figure 2. *Basement jointing at Austwick Beck Head.*

Norber Scar

The party then followed the limestone scars that climbed an anticline southwest of Crummack Farm. At the crest (767710) this anticline was seen to be largely due to post-Carboniferous folding, as the counterpart could be seen in the eastern slope of Crummack Dale (783713), but there was unresolved debate on the scale of any pre-Carboniferous hill of basement that forms the core of the fold. On the west side of Crummack Dale, the core of the anticline was seen to be strong greywackes of the Silurian Austwick Formation, forming ice-plucked crags just below the unconformity (768709). The party then walked downhill to emerge on the limestone bench of Norber, famous for its splendid glacial erratics of the Austwick greywackes sitting on plinths of Carboniferous limestone. These erratics had been carried south by the Crummack Dale ice, and are now stratigraphically higher than their source. It was however clear that the popular concept of them being glacially transported uphill from the floor of Crummack Dale was inaccurate, as they appeared to derive from the crags that were largely at a higher level within the core of the basement rise.

The party then perused the plinths on which the erratic blocks stood, and considered these as bits of limestone protected from postglacial rainfall dissolution by the blocks acting as umbrellas. Should this be the case, the heights of the plinths (up to 400 mm) indicate Holocene surface lowering of about 0.04 mm/year. The leader pointed out that this is comparable to surface dissolution rates calculated from solute loads in waters of the karst springs in the area, and is slightly lower than the rates of stream cave entrenchment in the limestone (0.08 mm/y) calculated from the ages of wall stalagmites. It is however lower than surface denudation rates in the warmer climates of Slovenia (0.065 mm/y), and substantially lower than the rate of valley-floor lowering in the glaciated troughs of the Yorkshire Dales (0.12 mm/y), calculated from stalagmite ages since caves were drained by glacial rejuvenations. Though protection of the plinths makes an attractive story, only a few of the many erratics do stand on plinths, and these may be largely ascribed to bench edges where erratics happened to be dropped on them. Also, the relationship of plinth height to the umbrella effect is weakened if dripwater runs round underneath some of the boulder faces; or this may explain why so few boulders stand on substantial plinths.

On leaving Norber, the base of the limestones was regained at Nappa Scar (769698). At first sight, the footpath appeared to lie along the unconformity; a metre of very coarse, poorly-sorted, debris with a carbonate cement forms the base of the scar above and on its north side, while slate is exposed along parts of the footpath. However, a scramble below the footpath reached scars that expose over 2 m of a mature, carbonate-cemented conglomerate with well rounded pebbles 5-10 mm across, that rests directly on the true basement unconformity over steeply dipping Ordovician slate. The slate exposed in the footpath is in loose blocks up to 2 m across, with structural orientation not as in the basement exposed below the scars (Fig. 3). The coarse deposits at footpath level were considered as a submarine landslide, or debris flow, formed shortly after marine invasion of the basement platform; concepts were mooted of it deriving from a weathered soil on a newly submerged hill (now cut by Crummack Dale), and of landslides triggered by activity on the Craven Faults. The origin of the conglomerate was unresolved, though it clearly derives from a quieter environment that was either fluvial or shallow marine.

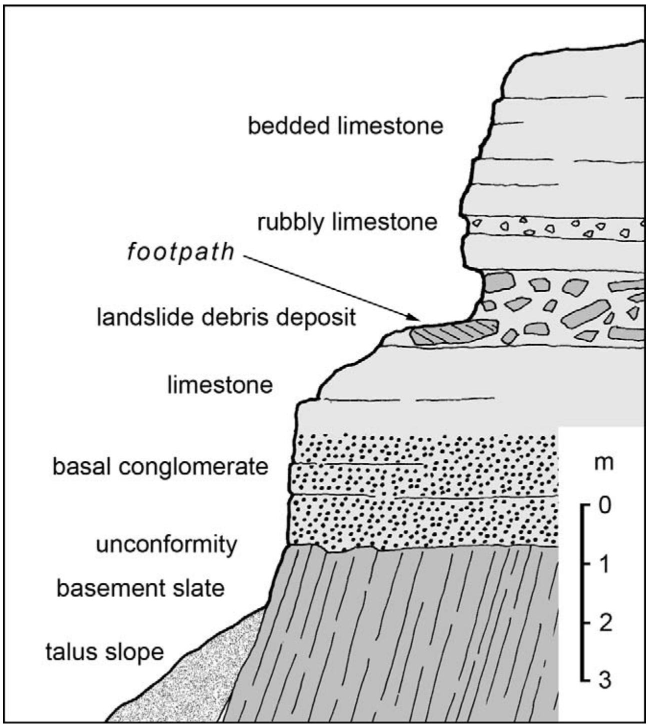


Figure 3. *Sketch section through Nappa Scar.*

Figure 4. *Flute casts exposed above Newfield House.*

An eastward walk along the valley floor, and a footpath above Newfield House then took the party to a viewpoint (798695) overlooking Dry Rigg Quarry. This works an annual 350,000 tonnes of the Horton Formation, valued as roadstone because of its resistance to polishing (PSV = 70-72). However, the quarry will close in 2009, after backfilling with all the waste fines so that the adjacent wetland can spread back over it, except for a part left as a deep lake beneath the high western quarry face. A descent to the southeast then took the party to some midfield crags (800693). These expose spectacular flute casts on the undersides of greywacke beds, the result of erosion and deposition by turbidity flows (Fig. 4). Units 400-1200 mm thick represent individual flows, and each is graded upwards from greywacke to slate with the flutes scoured into the top of each slate. Now dipping at over 70°, this turbidite exposure is a classic. It was then only a short walk to liquid refreshment at the Helwith Bridge Inn, except for the drivers who were despatched to recover the cars.

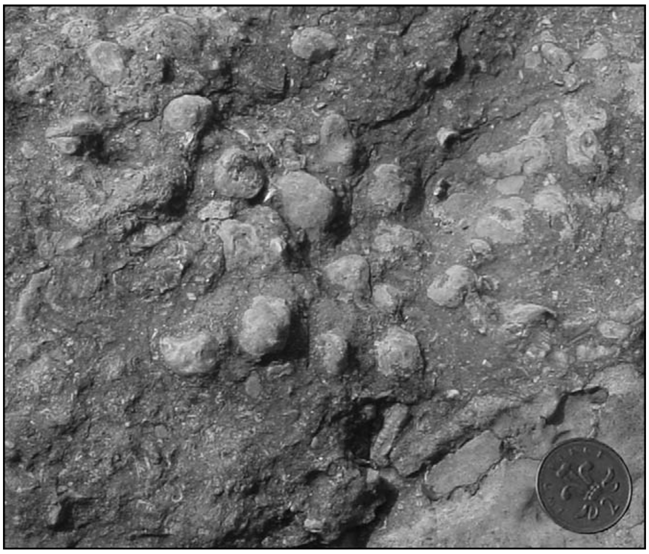


Figure 5. *Girvanella (or Osagia) at Lockey Gill.*

Sunday in the limestone

The party re-assembled at the head of Pen-y-ghent Gill (856733). A short walk down a footpath passed the fine karstic collapse known as Giant's Grave (857734). The downstream end of a cave up to 8 m wide along bedding planes has collapsed where its roof was only a bed about a metre thick and weakened by cross jointing. This is a rare case of a collapsed cave, albeit on a scale much smaller than Gordale or Cheddar (whose gorges are often mistakenly ascribed to such events). The party then turned into Lockey Gill, where an excellent exposure of the Girvanella Band was found just a few metres downstream of the road bridge (856735). This bed of black foetid limestone, just 300 mm thick and rich in the algal nodules the size and shape of almonds (Fig. 5), has long been used as a marker at the top of the Great Scar Limestone throughout northern England, though it is now mapped within the Hawes Limestone (the lowest of the Yoredale facies limestones of the Wensleydale Group) and locally forms more than one band. Though the algal nodules are distinctive, they are often only recognisable in weathered exposures. The bed may also be referred to as the Osagia nodule band, this being the correct generic name (from American localities) of the algae that creates the outer casing of the nodules (Johnson, G.A.L., 1958, discussion in Proc. Yorks. Geol. Soc., 114, 428-9).

A short walk onto the slopes of Fountains Fell then took the party to an unpublicised fossil locality in the Hardraw Scar Limestone. A stream section that exposes very fine shell beds of *Productus latissimus* almost directly overlain by coral beds of *Siphonodendron junceum* (perhaps more widely known by its old name, *Lithostrotion junceum*), offers insight into the fauna-rich environment of the Carboniferous shelf seas. The dry streambed below the exposure yielded blocks of *Siphonodendron*, but only fragments of the more spectacular coral, *Actinocyathus* (formerly *Lonsdalia*) *floriformis*, which was once common at the site (though not seen *in situ*).

Malham glaciokarst

The well-known Malham Cove was the next destination, approached the easy way with a walk down the Watlowes dry valley from Langscar Gate (888649). A high viewpoint on the east side of the Cove (see back cover) was the venue for discussion on its origins. The Cove is accepted as a feature that has retreated from a by-gone scarp on the Middle Craven Fault, which crosses the valley 600 m further downstream, but simple headward retreat of the karstic resurgence is not now regarded as viable. The flooded cave passage behind the Cove is about 6 m wide, and though it once took a flow larger than now, the stream's erosional power was small. It has only helped clear debris from the foot of the 70 m high Cove.

Subglacial and/or proglacial meltwater offers a better tool for fluvial excavation of the Cove and the Watlowes valley. Accelerated excavation by periodic jokulhlaups from an ice-dammed or sub-glacial lake within or beneath the Devensian ice sheet on the Malham Tarn plateau (as originally proposed by Alistair Pitty; pp 281-291 in *New directions in karst*, eds K.Paterson & M.M. Sweeting, 1986, Geo Books: Norwich) could account for the anomalously large sizes of both the Cove and Watlowes. In favour of fluvial excavation, the width of the Cove (so much greater than that of Watlowes) was compared to the proportions of the dry waterfalls among the coulees and scablands of Washington, USA, which were scoured by massive proglacial floods. Glacial action could involve ice plucking of the Cove wall where an iceway fed over the fluvially-notched fault scarp; this idea is supported by the reverse gradient over a hump (now cut by a post-glacial trench) on the thalweg rockhead immediately downstream of the Middle Craven Fault, and by the lack of any alluvial fan.

A lively discussion on the Cove could not be resolved, and the notion of polygenesis was regarded as attractive, with elements of fluvial, glacial and karstic erosion all contributing to evolution of the landform. Analogies were also made with the nearby Gordale Scar, where the wide lower section may share a genesis with the Cove, while the narrower gorge and waterfalls are meltwater features comparable to Watlowes, though the Gordale landforms are narrower due to headward retreat on minor faults that lie 70° clockwise from the line of the Craven faults.

After lunch in the warm sunshine, the party headed north, parked the cars above Selside village, and walked up the fell to Alum Pot (775756). Views down the 60 m deep shaft are almost obscured by trees, so the cave stream was pursued further up the fell. At the lower entrance to Upper Long Churn Cave, water could be heard in the cave beneath fissures that opened to daylight, and two cave entrances are provided by a breach in a dry ox-bow passage. Armed with a torch for each person, a careful venture into the upper entrance reached the stream after about 20 m of stooping. Upstream was then a delightful walk in a clean-washed canyon passage with flow-scalloped walls in pale limestone beneath a bedding plane roof that was the locus of cave inception (Fig. 6). How far members went up the streamway depended on their willingness to get wet feet or to climb over a few pools. About 300 m upstream, the chamber containing Dr Bannister's Handbasin was reached; some members climbed the inlet waterfall to emerge from the top entrance, while others returned downstream to enjoy the cave with eyes accustomed to torchlight.

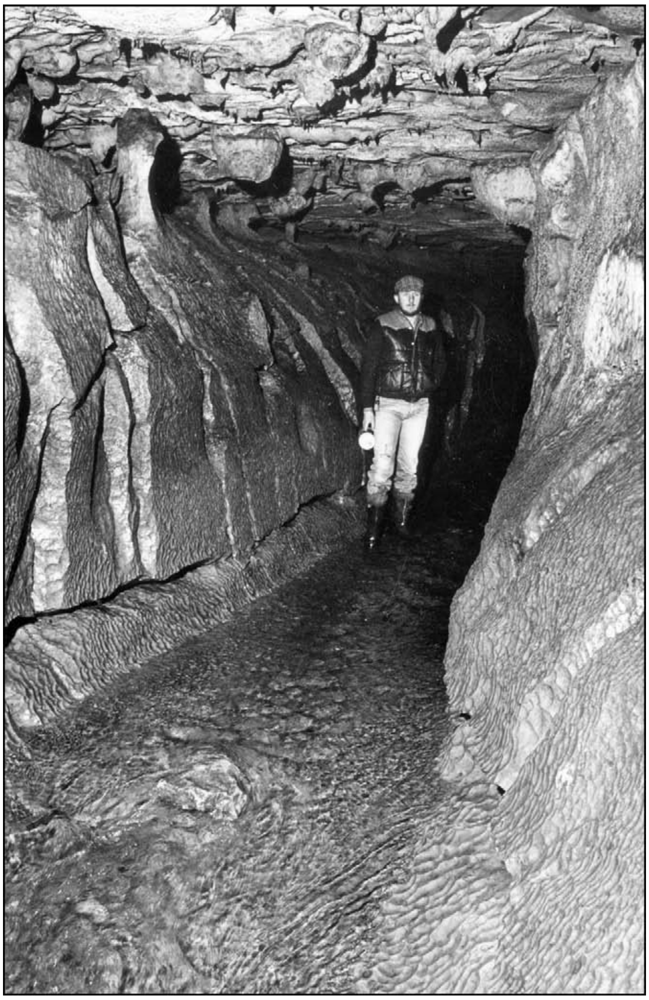


Figure 6. *The streamway in Upper Long Churn Cave.*

After a final look at the excellent limestone pavement (773756) between the two cave entrances, and a distant view across Ribblesdale to the splendid drumlins around Birkwith, members headed for the cars and journeys home. A vote of thanks was proposed by Tony Morris, before the leader thanked the Society members, and especially the contingent from the BGS, for providing erudite discussion, and thereby contributing greatly to an enjoyable weekend.

LECTURE

Building stones of Northamptonshire

Summary of the lecture given to the Society on Saturday 13th November 2004 by Dr Diana Sutherland, Visiting Fellow at Leicester University.

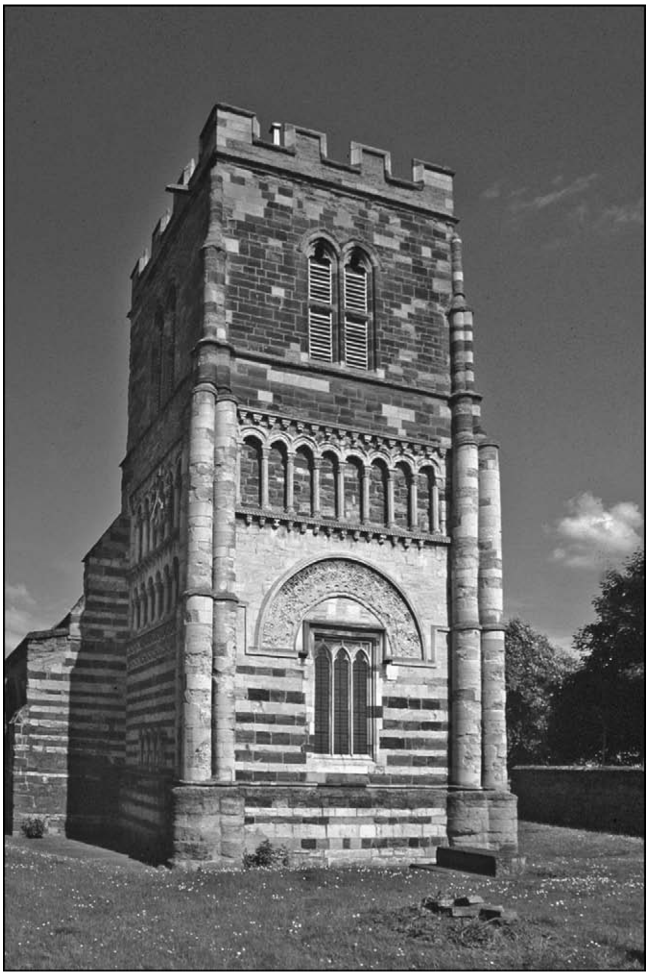
In 1712, John Morton, author of The Natural History of Northamptonshire, noted the great 'Variety of Quarry-Stone' and 'the Goodness and Plenty of it' encountered throughout the length of the county. He mentioned 'Quarries: here of White Stone, there of Red; here of Freestone, there of Ragg.' Few of those quarries remain today, but the stone that came out of them can be seen in the villages and market towns across Northamptonshire, yielding a great deal of geological interest. The building stones of such remarkable variety come from the sedimentary rocks of the Lower and Middle Jurassic, an array of ironstones, ferruginous sandstones and different limestones that occur interbedded with clays. The distribution and character of the various stones used in building provide a picture of the changing Jurassic paleogeography of this area of the East Midlands – distinct, in the Middle Jurassic for example, from the thick limestones of the Cotswolds.

Fieldwork in Northamptonshire many years ago established that the stone for village building generally closely matched the local geology. Vernacular buildings typically are built of rubblestone, roughly shaped blocks, in courses or randomly set in plenty of mortar, that came from the nearest stone-pit. Better-quality dressed stone for quoins, sawn ashlar with fine mortared joints, or carved mouldings, is not necessarily very local, though it mostly came from sources of freestone (a rock able to be worked freely in any direction) within a few kilometres. Until the later 19th century very little came from outside the county.

The formerly extensive cover of till and gravels has been dissected by the river systems, revealing Jurassic rocks in the western uplands and notably in the valley of the Nene and its tributaries. In ascending order, the formations that yielded building-stone are: Marlstone Rock (calcareous ironstone), the Northampton Sand (various ironstones, sandstones and sandy limestone), Lincolnshire Limestone (Collyweston 'Slate' and various limestones including Weldon Stone), the Rutland Formation (Kingsthorpe White Sandstone, and limestone that continues as the Taynton Limestone in the southwest), and the Blisworth Limestone Formation (locally a freestone).

The distribution of the different building stones is dependent upon geological factors. The deposition of the sedimentary formations was governed by changing paleogeography, related to fluctuations in sea-level and intervals of local non-deposition. Particularly noticeable is the absence of Northampton Sand in the east and southeast of the county; this marks the edge of the contemporary London-Belgian Landmass, where sediment was either not deposited or was subsequently removed during intra-Jurassic erosion. The Lincolnshire Limestone, providing excellent building stone, is confined to the north of Northamptonshire, thinning southwards, dying out by Kettering, and in places not reaching as far east as the Nene valley.

The distribution of the different building stones is most obviously linked to the gentle dip of the Jurassic strata to the southeast, accounting for the broad bands of successive formations across the county from the Marlstone Rock of the Lias in the west to the Northampton Sand of central Northamptonshire, with Blisworth Limestone as the main building stone of the east and south-east. The distribution pattern is further affected by the partial cover of glacial deposits, (although stone can be quarried from beneath a moderate overburden), and by the recent dissection of the terrain giving access to the outcrops along valley sides. The stone encountered in the villages across the county is governed by all these factors, but primarily the geological interest begins by looking closely at the stone, just with the help of a hand-lens.



The Norman church of St. Peter, in Northampton, built of ferruginous sandstone and ironstone from the Northampton Sand Formation, with Blisworth Limestone; the grave at the foot of the tower is that of geologist William Smith.

The Marlstone Rock Formation creates the prominent escarpment overlooking Warwickshire and Oxfordshire, and provides the rich brown building stone of more than 30 villages close to the outcrop in the west, from Kings Sutton to Ashby St Ledgers. As well as rubblestone, the rock is also seen as well-dressed ashlar, quarried for example on the estate for Edgcote House, built in 1752. The rock varies from dark ironstone near Byfield to ferruginous limestone nearer Daventry, and almost everywhere it contains fossils such as bivalves, brachiopods and belemnites, with indications of bioturbation, the product of a moderately shallow sea teeming with life.

Most of the brown stone villages of the county are built of a younger rock, the Northampton Sand Formation, which is separated from the Marlstone Rock by 60m of Whitby Mudstone (once a source of brick-clay). The Northampton Sand is extremely variable, and its local character is reflected in the many different types of building stone from the formation. The lower part, which may also be known as the Corby Ironstone Member, was extensively quarried for iron-ore from the 1850s to 1980, but in earlier centuries it was dug for building stone. The lowest beds which are usually sandy, sideritic and calcareous (a rock later rejected as ‘bastard stone’ in the iron-ore quarries) was favoured for building in the area north of Kettering, from Rothwell to Rockingham. Like the Marlstone Rock, it weathers from plum-coloured or greenish cores to a tawny colour. The overlying oolitic ironstone, where heavily weathered to dark limonite, made a durable building stone for churches and good houses in Finedon and Wellingborough from the 14th to the 20th centuries. Rare moulds of marine bivalves such as *Trigonia* are seen in the stone.

West of the Ise valley, the Ironstone Member is overlain by the ‘Variable Beds’, or Duston Member, which are chiefly limonitic sandstones once quarried in Northampton and Duston, and still worked at Harlestone. There are many examples of warm ginger-brown sandstone ashlar, such as the 18th century stables of Althorp, and Dallington Hall (where the geologist Samuel Sharp lived). North of Northampton a local development within the Northampton Sand provided a distinctive type of pale golden sandy limestone containing crinoid ossicles; once quarried as building stone in flat blocks known as ‘Pendle’, it gives a different character to villages such as Boughton and Pitsford. At Mears Ashby, the limestone bed was worked as freestone.

The Lincolnshire Limestone in the north begins with the sandy limestone, locally fissile, that was the source of the famous Collyweston ‘Slate’. The rest of the Lower Lincolnshire Limestone, used locally for building, is fine-grained, sometimes sandy, and seldom oolitic, The Upper Lincolnshire Limestone, conspicuously oolitic, provided the finest freestones; Weldon Stone is the best known variety, a porous oolite with small oyster shells, good for ashlar and mouldings, and used for many country houses.

Widespread erosion was followed by deposition of the Rutland Formation, the early Stamford Member providing the rare Kingsthorpe White Sandstone, locally containing rootlet markings. A bed of limestone, rich in oysters, thickens in southwestern Northamptonshire to continue as the Taynton Limestone; it was quarried at Helmdon to build Northampton’s 13th century Eleanor Cross.

Villages and market towns in the south and east are built of Blisworth Limestone, often micritic, but including spar-cemented rock with oyster shell and "superficial ooliths" (ovoid grains, with a thin calcite coating over shell fragments, which are usually more numerous than spherical ooliths). Freestone was obtained from Cosgrove Raunds, and good ashlar from near Oundle. Northamptonshire is noted for buildings of striped polychrome stonework, which combined the use of local dark brown Northampton Sand ironstone and Blisworth Limestone. The 12th century church of St. Peter in Northampton is a fine example, and is also interesting to geologists as the burial place of William Smith in 1839.

References

Morton, J., 1712. *The Natural History of Northamptonshire*. J. Knaplock: London. 608 pp.

Sutherland, D.S., 2003. *Northamptonshire Stone*. Dovecote Press: Wimborne. 128 pp.

LECTURE

The Dating Game

Summary of lecture presented to the Society on Saturday 5th March 2005 by Dr Cherry Lewis.

This is the story of how Arthur Holmes (1890-1965) learned to tell geological time. It combines the fascinating story of his life and his development of a geological time scale, with the history of geology and radioactivity until the 1950s. Despite a struggle against poverty, scientific hostility, ill health and personal tragedy, it was Arthur Holmes' vision of bringing chronological order into geological chaos that finally led to an accurate date for the Age of the Earth.

At the end of the 19th century, geologists, biologists, physicists and astronomers were looking for a clock that would provide an answer to one of the greatest time problems of all: how old is the Earth? Ingenious methods for measuring it were proposed, but few came close to the truth because no scale had been developed to quantify geological time. At that time, understanding geology was like understanding history, but without any dates.

From a good understanding of rocks and fossils, geologists such as Darwin thought that millions of years had passed between formation of the Earth, the start of Life, and the birth of Man, but they had no way of proving it and confounding those who believed in the short time scale implied by a literal interpretation of the Bible. Although geologists understood the order in which events had occurred, because there was no geological time scale, they had little idea of how old anything was geologically. Today we know that the Earth is 4.5 billion years old, and we can say with great confidence that an enormous meteorite collided with the Earth 65 million years ago, and wiped out most of life. But how do we know those dates?

Geologists have now developed their own clock with which to tell geological time. It is made of uranium and has been ticking away ever since the Earth was formed in a nebulous cloud of dust. In order to find out how long ago that was, all we had to do was learn how to tell the time using this special clock.

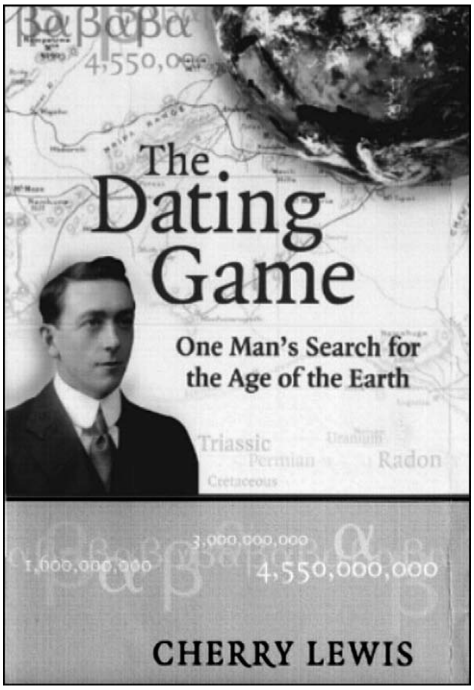
From a modest family background, Arthur Holmes went to school in Gateshead where he became fascinated by one of the fiercest scientific debates of all time: the Age of the Earth. An extremely bright boy, he won a scholarship to study physics at the Royal College of Science in London, where he worked on the new science of radioactivity which promised to shed light on problems of dating the Earth.

Undaunted by criticism of his work from established geologists (who were appalled by the results he obtained and by an Earth older than a billion years), his main opponent was poverty. Continually struggling against financial hardship he first took a job looking for minerals in Mozambique, and later on prospecting for oil in Burma, in an attempt to provide for his family. The extraordinary tales of life in these countries in the 1910s and early 1920s are recorded by him in diaries and letters sent home; he nearly died of malaria in Mozambique, and soon after the Burma company collapsed, his young and adored son tragically died of dysentery.

Back in Gateshead, desolate at the death of his son, with no money and no job prospects, life was very grim. He opened a shop selling Far Eastern trinkets in a business venture with his wife's cousin. But in 1924 Durham University decided to enlarge its science facilities, which included a new geology department. Arthur Holmes was chosen to set it up. A period of tremendous activity ensued, as decay rates of uranium isotopes were recognised and measured, so that the age of the Earth was pushed back first to 2 billion and then to 3.4 billion years, whereupon for a short while it was older than the age of the Universe as predicted by physicists. Arthur published his first real attempt at a geological time scale in 1927.

Then in 1931 on a geological excursion to Scotland, Arthur Holmes met Doris Reynolds. A brilliant geologist in her own right, it was a meeting of minds and they fell deeply in love. They married in 1938, soon after Arthur's first wife died of cancer.

As technology caught up with Arthur's ideas for a geological time scale, rocks could at last be accurately dated without using the laborious chemical methods that had previously hampered progress. By 1943, the true value of Arthur's work was finally recognised in his appointment to the position of Regius Professor of Geology at Edinburgh University, but he never lost sight of his vision. In 1953, the age of the Earth was finally established at 4550 million years. Give or take a few million, that number has not changed since.



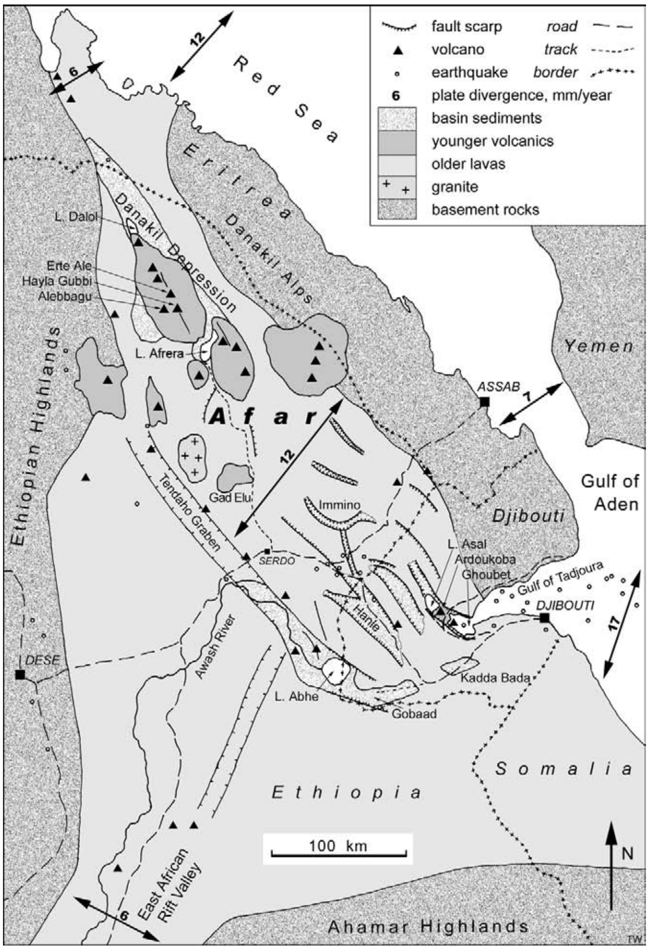
LECTURE

Extension tectonics in the Afar Triangle

Summary of lecture presented to the Society on Saturday 11th December 2004 by Dr Tony Waltham

Where the African Rift Valley meets the Red Sea, a triple junction of divergent plate boundaries has constructed the Afar Triangle, now forming parts of Ethiopia and Djibouti. Its terrain is a hot, barren, rocky desert. The African Nubian Plate forms the Ethiopian Highlands to the west, while the Danakil Microplate forms mountains between the Afar and the Red Sea. Within the Afar, the main rocks at outcrop are flood basalts, mostly < 2 Ma (see *Geology Today*, v.21, p.101-107, 2005, this author and title).

The largest of the grabens form splendid rift valleys across the waterless deserts, mainly within Djibouti. The Hanle graben is 3-10 km wide and 80 km long, with marginal scarps up to 800 m high flanked by smaller cylindrical faults on which blocks have rotated by up to 20°. The deepest graben contains the bay of Ghoubet and the saline Lake Asal (155 m below sea level), separated by the Ardoukoba volcano that has grown within the rift. The last eruption, in 1978, created a spatter ring, produced small lava flows from fissure vents, and left fresh fault scars along the margins of the subsided graben.



Major geological features of the Afar Triangle.

Travertine towers at Lake Abhe.

The most southerly graben contains Lake Abhe, fed by the Awash River and with no outlet, so that its level and extent fluctuate with climatic change. It is distinguished by hundreds of travertine towers that have grown over hot mineral springs when submerged by the lake waters. These stand up to 60 m tall, remnant from lake highs more than 1000 years ago that are also marked by terraces on adjacent hillsides.

All the Afar horsts and grabens are the result of active tectonic extension. Repeated surveying have shown that current divergence is more than 12 mm/year, and geological evidence shows that has been continuous for the last few million years. There is also up to 7 mm/year of extension on the Red Sea side of the Danakil Microplate. As the microplate moves eastwards, the horsts between the Djibouti grabens each have rotated about 11° in the last 1.8 Ma (measured by their basalts' paleomagnetism); this pattern of movement may be graphically described as bookshelf faulting. Accurate surveys indicate that about 80% of the crustal extension is accommodated by magmatic emplacement, as dykes and lavas, while 20% is expressed in the normal faults of the grabens.

Towards the northern apex of the Afar Triangle, the Danakil Depression descends to about 120 m below sea level, and is therefore especially hot and arid. It is inhabited by the tough and fiercely defensive Afar people, and is rarely visited by Europeans. A journey into it is a minor epic, requiring a pair of 4WD vehicles with a support team of Afar tribesmen. The floor of the Depression has salt lakes (exploited for their minerals) in basins fringed by Pleistocene reef limestones and underlain by 1000 m of evaporites, all formed when it was a subsiding and progressively desiccating arm of the Red Sea.

In the Depression centre, the active basaltic shield volcano of Erte Ale rises to 730 m above the salt lakes. Its summit caldera contains pit craters, one of which houses an active lava lake. One of the few long-lived lava lakes in the world, the lake's continued existence relies on heat flow from rising magma that only rarely overflows as lava, but is nearly all lost into active dyke swarms that underlie this constructive zone of plate divergence. For the last few years, the lava lake has been only 30 m across (see back cover), but it makes a fine climax to a journey into the Afar.

REVIEWS

Sedimentary Rocks in the Field, by Dorrick A.V. Stow, 2005, Manson: London. 320pp, 471 figures (424 colour photos), ISBN 1-874545-69-3£19.95

Clear observation in the field is a basic geological skill, but it needs systematic recording and integration to bring out the underlying mechanisms and processes if field trips are not to be just another form of visual stamp collecting - enjoyable but not really productive. Professor Stow of Southampton University provides a teaching guide to sedimentary rocks (with recognition and recording of their principal features) in a structured style that enables field interpretation and allows development of subsequent laboratory studies.

Preliminary chapters give a sound introduction to basic field techniques and the principal composition, structures and textures of sedimentary rocks, followed by individual chapters on each type of sedimentary rock. In the last section of the book, facies cycles, architectural elements and facies associations are described, interpreted and compared with sequence stratigraphy. Finally, there is a valuable synthesis of the diagnostic data of depositional environments gathered together in twelve standardised tables. The text is built round more than 400 excellent colour photographs, with a brief description of each to emphasise teaching points. These are complemented by well-chosen line-drawings and tables to make a rounded and remarkably complete guide. The sections on trace fossils and carbonates are especially attractive, but dip anywhere and there is not a dull page in the book. There is a useful appendix with mapping symbols, grain sizes, comparator charts, sediment description check list, stereonet templates and updated stratigraphic timescale and nomenclature.

Books such as this inevitably draw on the work of others, and Stow has selected but modified much material and enhanced its presentation. There is a reference list given entirely to standard sedimentary text books. Disappointingly, 13 text references are not in the list and Fig. 3.13 showing “Standard sequences in different depositional sequences synthesised from original sources” should have had those sources specified, since the book is aimed at those who may wish to amplify details of sequences of which they have been previously unaware.

Clearly, Professor Stow is an excellent teacher and the lucky students in Southampton must have splendid field trips. This is an outstanding book, surely destined to be a classic, whether to take into the field or read by the fire on a wet winter night. With 320 pages on glossy paper the book weighs 0.7 kg. It is a bit heavy for your geriatric reviewer's rucsac (and it would be a shame to get it wet and spoil the pictures), but a copy will be kept in the glove compartment of the car as a field trip necessity. It is recommended unreservedly: buy a copy now before there is need for a reprint.

Gerard Slavin

Geology of the Lincolnshire Wolds, Lincolnshire Wolds Countryside Service: Lincoln, 2004. A3 sheet, free from 01507 609740 (or EMGS Secretary).

This full-colour folded leaflet is one in a series, *Wonders of the Wolds*, produced in collaboration with the county's RIGS group. It introduces the geology of the Wolds and expands it further under the three headings of landscape and geology, glaciation, and soils and use. There is a very clear but simplified geological map covering the area from Spilsby in the south to Barton on Humber in the north, showing the location of roads and villages. Four types of drift deposits are shown, and the solid geology is simplified to four types of rocks; all eight materials are explained and described. Twelve specific areas of interest within the Wolds are identified, and the geology of each is described; these vary from museums to nature reserves to topographic units. Where appropriate, the access arrangements are described. A few of these were visited on a recent EMGS field trip led by John Aram, who was also involved in this publication. The leaflet is a model of how much information can be packed into a small and accessible document. It is obviously aimed at the interested tourist, but a day out visiting some of the locations in this scenic area would be rewarding and interesting for any EMGS members.

Alan Filmer

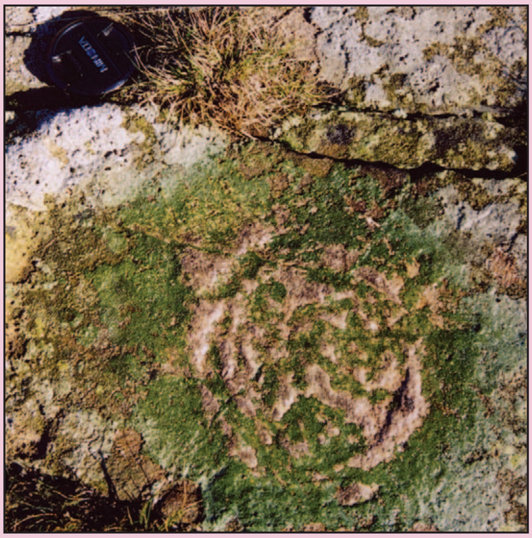
Collieries in the North Staffordshire Coalfield, by Paul Deakin, 2004, Landmark: Ashbourne. 160 pp, ISBN 1-84306-138-4, £19.95.

While there is not much geology in this welcome addition to the Landmark Collectors Library of mining history books, it will be of interest to any EMGS members with a coal-mining background. It is a photographic atlas of some 30 collieries, providing a record of a vanished industry in nearly 300 photos. Both surface and underground views are included, together with a few opencast sites. Many photos are in colour and demonstrate the author’s mastery of photography in difficult conditions. They are well chosen to illustrate working methods, haulage and ventilation systems, and aspects of miners’ lives underground. The photographs were taken largely in two periods, the 1950s and 1980-90s, with a handful of early pictures of special events. While most are by the author, other contributors include Bob Metcalfe and Albert Baines-Davies. Captions include some details of the collieries’ life and history; shaft depths are given in most but there are few details of which seams were worked. While the book does not set out to be a history of the Potteries coalfield, an introductory chapter on the coalfield with an area map would have improved it. The last few pages are recent views of the sites where collieries were once working, some less then 10 years ago. Now housing estates or agricultural land, they demonstrate how quickly all traces of a once dominant industry can be erased from the landscape.

Trevor Ford

Blackbrookia oaksi, p.76

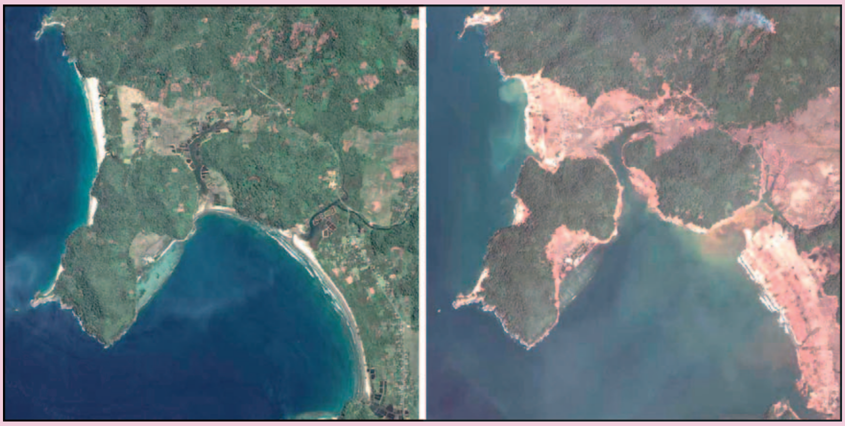
Malham Cove, p.147



Ivesheadia lobota, p.76

Erte Ale lava lake, p.151

Before and after the tsunami in Sumatra, p.103



Shap granite, p.118