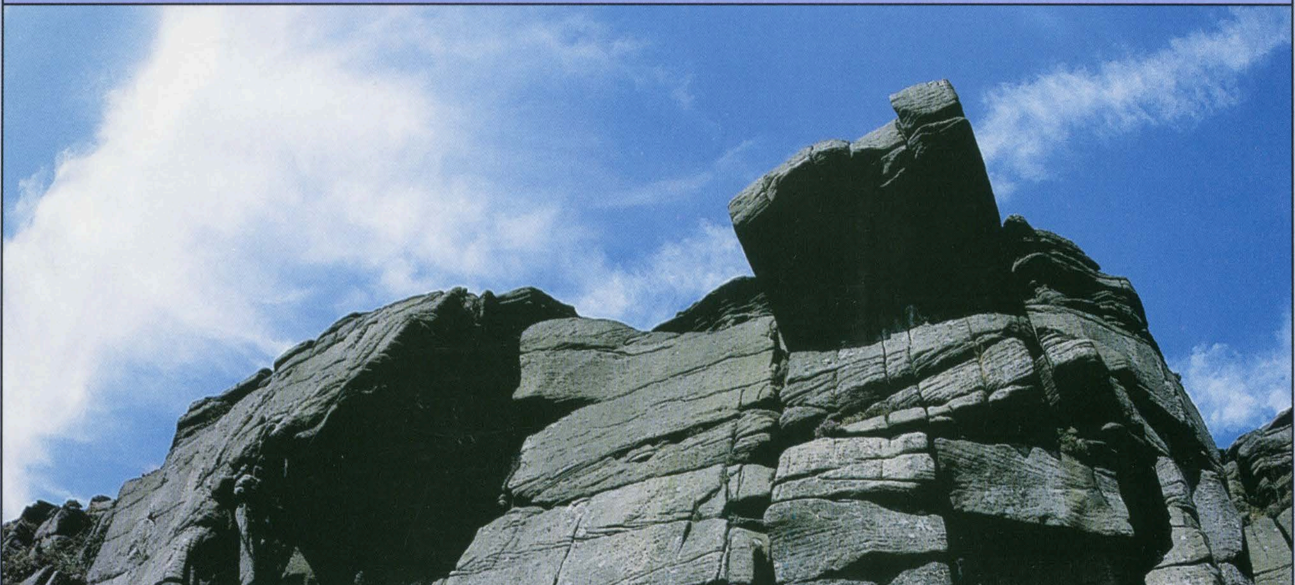
MERCIAN
Geologist



The Journal of the East Midlands Geological Society

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East Midlands Geological Society

Address for Correspondence
The Secretary, E.M.G.S.
Rose Cottage, Chapel Lane,
Epperstone, Nottingham NG14 6AE
0115 966 3854 alan.filmer@which.net

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Cover photograph: The quarried and weathered face of Stanage Edge in the Derbyshire Peak District, with incomplete grindstones left below where they were worked from the massive beds of the Namurian Chatsworth Grit [photo: Tony Waltham].

Contents

MERCIAN NEWS

Lincolnshire glacial erratics

Exotic erratics were carried to Lincolnshire by Pleistocene ice that originated in Northern England, Scotland and Scandinavia, and some of their more distinctive lithologies allow accurate identification of their sources. Last century the Lincolnshire Naturalist Union had a Boulder Committee who started to make a survey of erratic boulders in Lincolnshire. Since those days, deep ploughing and the construction of new buildings and roads has brought to light many more boulders than were known at that time. In the new millennium, and shortly after the centenary of the foundation of the LNU Boulder Committee, now seems to be an appropriate time to update this information.

The Lincolnshire RIGS Group has produced a leaflet, *Gifts from the Ice Ages*, that encourages residents and visitors to report any stones 'foreign' to the county. The response has been encouraging and these initial reports are all investigated by the RIGS team, to compile an updated record of the county's erratics. For copies of the leaflet, or with reports of erratics, contact RIGS on 01507 526667 or at Lincolnshire Wildlife Trust, Banovallum House, Manor House Street, Horncastle LN9 5HF.

Tales from the web site

The EMGS web site, constructed and maintained by Rob Townsend has been operational for a year, hosted by the Natural History Museum, which also hosts other societies and organisations with aims similar to those of the Museum itself. The site contains an invitation to join the Society, current programmes of lectures (together with abstracts) and field trips, details of the Society's publications and links to other geological societies (who also have links back to the EMGS). The site is becoming better known and has also prompted new members to join the Society.

Requests for information are now reaching the secretary through the site. One from the USA was trying to locate a copy of a Mercian Geologist paper by CJ Duffin in 1979. This was provided, and the author was also located through the web so that the Atlantic is now being crossed by e-mails on the finer details of coprolites from Rhaetic bone-beds.

Another request was from someone, also in the USA, researching the life of a child killed in an air raid in 1943 when leaving the shelter of the Broad Marsh caves. A reply outlined the structures that existed prior to building the shopping centre (along with a promotion of the EMGS book on the caves).

Why not visit our site (at www.emgs.org.uk). The more people who do so, the better the site will become known. The secretary welcomes members' suggestions for any material that it should include.

Peterborough Museum

It is well known that Peterborough Museum possesses a collection of Jurassic marine fossils matched only by those at the British Museum of Natural History and the Hunterian Museum in Glasgow. The collection has been augmented and cared for over a period of 18 years by volunteer members of Stamford and District Geological Society, led and inspired by Alan and Pauline Dawn. The conservation laboratory is well established, and this year has been augmented by an airbrasive machine, purchased with contributions from many sources, including a generous grant from the EMGS.

An airbrasive machine is an invaluable tool in fossil treatment. It sends a blast of compressed air and abrasive powder through a very fine jet that is directed to remove rock from around the fossil being prepared. Powders of various grades and hardness can be used, according to the hardness and delicacy of the specimen under treatment. Work with the air jet is slow and tedious, and is sometimes carried out under magnification in a dust cupboard, with an extractor fan to expel surplus dust. It is more gentle and controllable than the normal mechanical methods of fossil preparation.

Demonstrations of the machine in operation can be arranged. Contact the museum at Priestgate, Peterborough PE1 1LF or telephone 01733 343329.

Rockhound Challenge 2000

Thirteen-year-old Kirsty Pepper from Spalding, created an imaginative and accurate applique of a Jurassic underwater scene to carry off both the 12-16 Rock Artist Prize and the overall Rockhound Challenge Winner 2000 trophy. Also from the margins of our region, Sean McMahon from Huntingdon shared the first prize in the 12-16 Rockhound collector competition, with his personal account of how, since the age of six, he had gathered his impressive fossil collection. Both received their prizes in December at Somerset House after a tour of the Gilbert Collection, with its truly fantastic pictures, furniture and items made of beautiful and rare, precious stones, gold and silver.

Editorial

Members may be pleased to note that the front cover of the Mercian Geologist has returned to the East Midlands *Geological Society*. The editor can only apologise for the classic typographical error in the previous issue. Now that the journal is back in the geological world, members are invited to contribute to it with any news items, reports, papers or reviews that can bring to life the geology of our home region. Especially welcome would be a member's photograph for the front cover.

GEOBROWSER

Recent geological findings from around the world, selected from the current literature

Message to the burning Bush

The ‘global warming’ debate reported in our last issue has been given a wide review in the Oklahoma-based *Oil & Gas Journal* (August 28th, 2000; p.58). This even-handed article opined that the Intergovernmental Panel on Climate Change (IPCC) has so far failed to provide ‘compelling’ evidence about the extent of human influence on global climate, although a re-assessment is due this year. Countries like the UK are nevertheless attempting to reduce greenhouse gas emissions in line with their Kyoto targets, although others will be allowed increases of up to 27%. New Zealand is meanwhile concerned that sheep are emitting methane to the tune of 45% over 1990 levels.

The article’s prophecy, that during the first years of the next US administration ‘......the Kyoto target will be declared unworkable’, was duly fulfilled by incoming President George W. Bush, but the cancellation of the committment was probably down to politics: the growth of US industry is currently outstripping the availability of power supplies and the new President was the governor of oil-rich Texas. The uncompromising nature of the presidential stance may not be universally reflected in US commercial circles, however, as indicated by the *Oil & Gas Journal* article’s conclusion that the petroleum industry must have the ‘courage to accept the challenge’ by actively supporting the development of alternative fuels and research into global climate change. This message carries some weight because the article was written by a former Vice President of Texaco and head of delegation for the International Chamber of Commerce to the UN Framework Convention on Climate Change, although it may be significant that it was written two years after the author’s retirement.

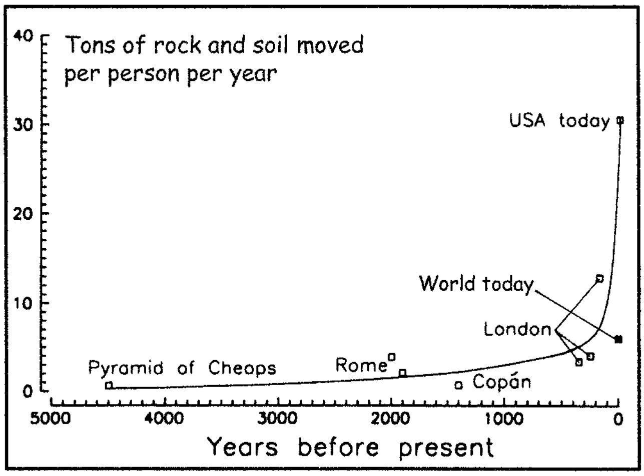
Existential geology: *where do we come from?*

The evolution of primates into *Homo sapiens* is now well documented, but where did Life itself begin? Theories about this were reviewed in the *Journal of the Geological Society* (1997, p.377), starting with the ‘warm little pond’ of Darwin (1888, p.18) through to the complex experiments of the 1980s that achieved the synthesis of DNA by replication using peptides, in a process called polymerase chain reaction. Those experiments showed that the chain reactions of Life needed water, they needed warmth, and they needed sites to concentrate and combine together the key ingredients and molecular components at an early stage. The crucible of Life, the article argues, could have been provided by a fundamental component of plate tectonics that certainly existed in Archaean times: the mid-ocean ridges, and specifically the mineral-rich and gas-rich hydrothermal systems of the black smoker chimneys. Modern ones are hosts to an abundance of primitive life-forms but it is their structure, consisting of small interlocking compartments with walls of porous, sulphide membranes, that is of particular interest. In identical ancient chimneys, it is suggested, the ingredients for organic synthesis could have diffused into the compartments, generating simple amino acids in concentrations that would favour the development of self-replicating peptides, RNA and DNA. Over billions of years these simple cells could evolve into organisms robust enough to migrate from the oceanic ridge and colonise the shallower seas, some perhaps being forerunners of the *Charnia*-type species that first appeared at around 580 Ma. The discovery (*Geology,* 2000; p.731) of organic material in analogous Early Archaean (3235 Ma) black smoker sulphide deposits may therefore be evidence of our own humble beginnings.

Existential geology: *why are we here?*

Living organisms have made important contributions to the stratigraphical record: witness the shell, coral and algal-rich Carboniferous limestones of the Peak District, and Cretaceous Chalk strata constructed of billions of coccoliths. Humans, on the other hand, stand accused of warming the atmosphere and raising sea-levels to the extent that parts of the landmass will eventually disappear. This negative press is, however, countered by some unusual research (*Geology, 2000*; p. 843), which argues that humans are now the ‘premier geomorphic agent sculpting the landscape’.

Our efforts can be quantified in terms of a graph showing tons of earth moved per head of the estimated population, plotted against time. The



Estimates of the amounts of soil and rock moved intentionally by various relatively advanced societies in the past (courtesy of Roger Hooke, Maine University).

figures have been calculated to include the pyramid-building ancient Egyptians, 4500 years ago, although the earth certainly moved for the iron-age Egyptians, who constructed a forerunner to the Suez Canal that by 600 BC was 60 m wide and 13 m deep. The graph of earth movement shows a slight gradual rise until about 1800 AD, when it soars vertically upwards. The advent of the Industrial Revolution is the obvious reason for this, as is the expansion in agriculture, which caused vast amounts of soil to be washed away ('moved unintentionally'). Currently, Americans are shifting about 30 tons of earth per person annually, against the average figure of 6 tons worldwide.

The bottom line is that the total amount of earth moved by our ancestors in the past 5000 years would be sufficient to build a mountain range 4000 m high, 40 km wide and 100 km long. Moreover, it is apparently our destiny to double the length of that hypothetical mountain range within the next 100 years.

Dinosaur theories

Within the science of geology, theories go into dinosaur-like extinction and are replaced by newer ideas avidly researched and supported in band-wagon fashion. But some old theories only fade into the background, and, like the coelacanth, wait for rediscovery. The continuing debate over mass-extinctions at the K-T (Cretaceous-Tertiary) boundary is a case in point. The magnificent Doomsday scenario at the end of BBC's *Walking with Dinosaurs*, showing the fireball and ensuing dust-laden 'winter' that destroyed those creatures, represents the zenith of the meteorite-impact theory of Alvarez et al., (*Science*, 1980; p.1095), but the old ideas of more gradual extinctions are resurfacing.

A review in the *Journal of Earth Sciences* (2001, p.239) has concluded that the extinctions were, as hinted at long ago, part of a 'multicausal event', linked to sea-level fall and global environmental changes brought about by the disruption of oceanic circulation patterns etc. In other words, some biotic populations were under stress before the end of the Cretaceous, but the revised 'gradualist' theories are now suggesting that this stress was exacerbated by superimposed, sudden events. This new stance is necessary because even the most impact-sceptic gradualists would attribute an increment of stress to the Chicxulub meteorite strike 65 million years ago. In addition, however, the end-Cretaceous Deccan basalt eruptions in India are also being implicated in precipitating the mass extinctions. The influence of this event is tangible, for the Deccan ash clouds may be responsible for worldwide layers rich in *volcanic* iridium (Ir), which are only now being distinguished from *cometary-derived* Ir layers and were probably confused with the latter in some earlier papers.

The Deccan sequence assumes further significance in that its sediments contain terrestrial dinosaur faunas, and accurate radiometric dates obtained on the lava flows constrain the age of these fossils (*Journal of the Geological Society*, 2000; p. 257). A protracted eruptive history has been revealed, lasting from 68.7 to 61 Ma, but with no dinosaur remains above Basalt Flow IV, dated at 65.1 Ma. So the dinosaurs survived the earliest Deccan eruptions, but were they edged into extinction by the cumulative effect of ash clouds from the later outflows, or by an adverse climate created by the Chicxulub impact on the other side of the world, or a combination of the two events? The only certainty is that the critical fossil-bearing exposures will be examined in ever-greater detail as the reconstructed gradualists argue it out with the catastrophists.

NEWS from the BGS

Environmental impact

The winter of 2000-2001 will enter the record books as one of the most miserable ever in terms of environmental crises. Unprecedented levels of rainfall have led to flooding in many parts of the country (see p. 126 of this volume), and saturated soils and bedrock have resulted in a record number of landslips. Many of these have affected transport networks already under stress from flooding and the aftermath of the Hatfield train crash in October 2000. One person died and a second was seriously hurt when their car was overturned and crushed by a coastal landslip at Nefyn in North Wales, and a major tragedy was narrowly avoided on the Isle of Wight when a mudslide crashed through the walls of a packed seaside hotel. Many experts predict that this winter has provided just a foretaste of the perils to come from global warming. Could we have been better prepared to face these events? An All-party Parliamentary Group for Earth Sciences, assisted by BGS and the Geological Society of London, has been attempting to answer this very question by taking a hard look at issues such as availability of strategic data and advice, levels of co-operation between Government agencies and the effectiveness of the planning system. Hopefully, in the future, the nation can avoid such crises before they happen by establishing both improved strategic planning and safer use of land.

Foot and Mouth

At the time of writing, the Foot and Mouth epidemic has brought BGS fieldwork programmes to a standstill. Surveys in rural areas remain suspended, and mapping in urban areas is only proceeding following rigorous risk analyses on a case by case basis. One of the most serious problems associated with the crisis has been the need to identify safe burial sites for the huge number of livestock carcasses generated by the MAFF slaughter policy for containing the Foot and Mouth virus. BGS has employed the latest digital mapping and Geographic Information Systems technology to help the Environment Agency, MAFF and the Army select the most suitable sites for shallow burial of carcasses. Suitable sites must be easy to excavate and should offer 'natural containment' of any potential contaminants to protect groundwater supplies and surface water courses. GIS has been used at the regional scale to provide the Environment Agency with maps showing areas of suitable geology, allowing the Agency to then import their own environmental protection and planning data to narrow down the range of potential sites. BGS has then followed up with detailed geological assessments to help determine the environmental risk at each potential site. These measures should ensure that the Foot and Mouth crisis does not leave a legacy of environmental contamination long after the end of the virus outbreak.

FROM THE ARCHIVES

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

The plankwalks at Hawton Quarry

Operated by Cafferata and Company of Newark, Hawton Quarry was at its time the largest gypsum quarry in Britain. The quarry face was first loosened by blasting, and the gypsum was then excavated by hand and loaded onto railway wagons hauled by locomotive. By the 1930's, 'electric navvies' and cranes were introduced to extract and load the ore. The very precarious-looking planks were used by the quarrymen to walk barrows of waste 'marl'. This was stripped from benches in the working face, and carted across the planks to backfill the quarry. The site was excavated beneath the Devon valley alluvium and needed steady pumping to keep it dry.

This photograph of the workings was taken on 9 May 1911 by the celebrated Survey photographer, Jack Rhodes (see his short biography on page 6 of the last issue of Mercian Geologist).

The Hawton site exploited mineral from a series of gypsum beds known collectively (and perhaps unsurprisingly) as the Newark Gypsum. This occurs

Hawton Gypsum Mine, Newark. in 1911 (BGS photograph # A1189, © NERC) within the top part of the Mercia Mudstone immediately below the Blue Anchor Formation, and contains workable mineral in a belt extending from Cropwell Bishop to Newark. The Newark Gypsum consists of up to a dozen individual seams each 0.1 to 0.5 m thick and spanning a stratigraphical interval of up to 20 m. Large gypsum nodules up to 1.5 m thick and 4 m across occur at the top of the series. Each seam was individually named by the quarrymen and is distinctive in terms of features such as thickness, lateral persistence, colour and purity.

In the early 20th century, gypsum was put to a variety of uses. It was principally employed in plaster and cement manufacture, as a filler in various substances, notably paper and paint, and as a 'finisher' in the manufacture of cotton and lace goods. It was also used in brewing and as a fertiliser, particularly by hop growers in Sussex and Kent. The pink varieties were sold as an ornamental stone for use in grottoes. Gypsum continues to be an essential raw material for most of these uses today, although its use as a fertiliser has substantially declined. Other more specialist uses of gypsum include ceramics, dentistry, food additives and surgical plaster (perhaps handy to mend the fractured limbs of fallen quarrymen!).

The Newark Gypsum has been mined, usually by surface quarrying, at several places in south Nottinghamshire, including the Balderton and Hawton areas to the south of Newark, and at Staunton in the Vale, Orston and Cropwell Bishop. Other mines southwest along the outcrop, at Gotham, East Leake and Barrow on Soar, exploit the Tutbury Gypsum at a slightly lower stratigraphical level. This occurs as a single seam up to 5 m thick, which is usually mined underground by the pillar-and-stall method.

Total gypsum production in Nottinghamshire was around 100,000 tons annually at the time of the photograph. By comparison, current annual production of gypsum in Britain is about two million tons, of which Nottinghamshire contributes about one half. Much of the demand for plaster, plasterboard and cement-making are now satisfied by DeSulphoGypsum, a by-product of Flue Gas Desulphurisation plants at coal-fired power stations. The FGD plant at Ratcliffe-on-Soar produces about 250,000 tons of gypsum per year. Demand for natural gypsum will continue for the more specialist uses, and can only be satisfied by the higher purity mineral yielded by the Newark Gypsum. The seams are currently quarried at Kilvington, mid-way between Bingham and Newark. That quarry will probably be exhausted in 2003, after which production is planned to return 'home' to Newark - with the re-opening of the currently mothballed mine at Bantycock, south of Balderton.

Andy Howard and Paul Tod
British Geological Survey; kwphoto@bgs.ac.uk

THE RECORD

The Society has welcomed 28 new members, and membership numbered 384 at the end of 2000.

Field meetings

In May 2000, Ian Chisholm led a day trip to Stanton Moor, Derbyshire, to examine landforms on contrasting facies within the Namurian gritstone.

In June, Andy Howard led an evening trip around the University campus to look at the Nottingham Castle Sandstone sequence.

In July, Albert Horton and Keith Ambrose led a visit to Upper Broughton Church and the nearby Marlstone in Leicestershire.

Also in July, Neil Aitkenhead led an excursion to Carsington reservoir and the dolomitised limestone in the slopes up to Harboro' Rocks.

In September, Dave Elford led a visit to the quarries in Scunthorpe Ironstone.

In October, Alan Dawn led a day excursion round three quarries in the Lincolnshire Limestone between Wansford and Duddington.

In February 2001, Tony Waltham led two evening visits to the sandstone caves under the Broad Marsh Centre, including some that are not normally accessible.

The indoor meetings

In March 2000 after the AGM, Dr Martin Whyte related experiences chasing dinosaurs across China.

In April, Prof. Mike Rosenbaum talked about the role of geology for the military in wartime.

In May, as part of Derby Environmental Week, Dr Trevor Ford delivered his authoritative lecture on the history and geology of Blue John fluorspar.

In October, Dr Tony Waltham described the geology and volcanoes of Kamkatka at a meeting attended by 130 people.

In November, Prof. Dick Aldridge gave a most lucid talk to bring us up to date on the progress of his research on conodonts.

In December, Trevor Bridges explained how the form of minerals reveals something of their history.

In January 2001, Dr Tony Reedman talked about the BGS activities in the developing world.

In February, Dr Chris Lavers gave a fascinating talk on past extinctions and drew parallels with man's activities today.

Events

The Society was represented at the Geologists' Association's Earth Alert in Brighton, at the Cresswell Crags road show day on Archaeology and Geology, at the Millennium Wall event at the National Stone Centre, at the Derbyshire Country Capers and at the British Sedimentological Research Group meeting at Loughborough.

Alan Filmer, Secretary

The Source of the Woodhall Spa Mineral Water

Michael Czajkowski

Abstract. For over 80 years the town of Woodhall Spa developed around a unique source of water rich in iodine and bromine, which was found during sinking of a trial coal shaft in 1821. No attempt was made to determine the source of the water, until the Spa was established and the shaft had flooded. Various published suggestions for the source of the water included a direct marine connection and origins in beds from Triassic to Upper Jurassic. Lining of the shaft has prevented direct examination. Assessment of the often conflicting documentary and well log information available, suggests a source of the Woodhall Spa mineral water, in the Kellaways Sandstone. Much unpublished material only became available with the creation of the Woodhall Spa Cottage Museum archive.

The village of Woodhall Spa lies three kilometres east of the River Witham midway between Lincoln and Boston, with the sites of the Spa Bath and various wells and boreholes within and close to the village (Fig. 1). The Woodhall Spa Bath shaft was the last of several sunk in pursuit of coal resources under Lincolnshire in the early 19th century (Czajkowski, 2001).

It was started in 1821, and was lined with brickwork for most of its 256 m depth. There was no contemporary record of the beds passed through during the excavation, and the shaft was abandoned in 1823, after additional boring had reached a total depth of 366 m. Afterwards, the shaft quickly flooded, largely due to inflow from a fissure encountered during the sinking.

The water rapidly gained a local reputation as a healing spring for gout-related illnesses and arthritis, after the overflow had supposedly cured cattle who were drinking it. This prompted the Lord of the Manor to build a small bath house, completed by 1834. Later, under the advice of Dr. A. B. Granville, author of *The Spas of England and Principal Bathing Places* (1841), he had the water analysed, and found that it was strongly saline and was unusually rich in iodine and bromine (see below, Table 4).

With the expansion of the railways, the embryonic Spa rapidly gained a national reputation for its curative properties, and by 1860 had developed into a major spa complex, around which the modern village developed. In the 1880s, increased usage and slow recharge of the spa water into the shaft prompted attempts to increase the supply by excavating horizontal adits from the shaft. After the First World War the spa water industry declined, but the Woodhall Spa Baths continued in use. The National Health Service operated the site as a rheumatism clinic, using the saline spa water until 1971, supplemented by mains water until the collapse and infilling of the shaft in 1983. Currently the site is derelict. Debris from the spa buildings were bulldozed into the shaft as fill.

Following the unexpected initial success of the original Spa Bath Shaft, other wells were sunk to obtain the mineral water. A deep bore was also drilled nearby, in a search for oil in the 1940s. These have all contributed towards resolving the conflict between the various theories on the geology of the Spa Bath Shaft and the source of the Woodhall Spa mineral water.

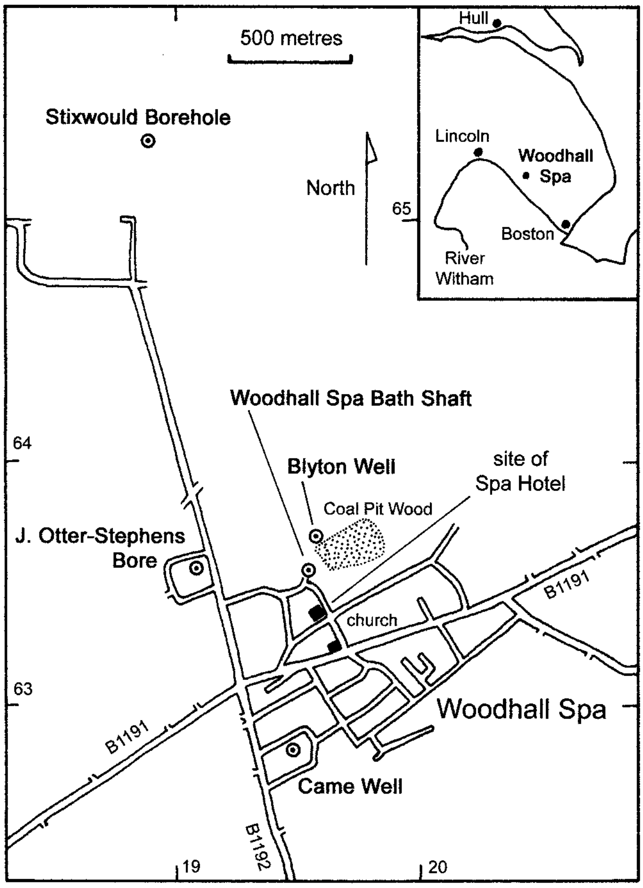


Figure 1. Locations of the shafts and boreholes referred to in thetext, in relation to the modern village of Woodhall Spa.

The Woodhall Spa Bath Shaft

The original shaft

This lies on the north side of the village (at NGR 197636, 8.6 m OD; Fig. 1). The earliest published record on it is from Granville (1841), who gave the depth of the well shaft as 280 yards, which was then bored for a further 120 yards (365.8 m in total). He stated that the source was "a brine spring encountered at about 170 yards" (155.5 m), and also that "17 or 18 feet is through a soft freestone rock from whose surface brine-water has been seen to percolate constantly". It was this water that became the Woodhall Spa mineral water.

Granville seems to have been a careful researcher and when he visited the Woodhall Spa Baths in 1838-39, presumably to gather material for his book, stimulated Mr Hotchkin, the Spa Bath owner, to have the water origin investigated and analysed. Two statements by workmen (Belton and Cheeseman, 1839), who worked to contain the flooding, were recorded at that time.

Cheeseman stated that the shaft was 303 yards deep (277 m), and the base of the source rock was at 180 yards (164.6 m). He also stated that water oozed from every part of the source rock, but especially from a deep fissure, the water flowing east-west, and "This rock which was a soft spongy grey stone and easily cut with a knife, in fact it kept continually falling in masses into the shaft during the operation and is 18 yards thick". The source rock section of the shaft was lined with cemented brickwork, and a conduit was built to convey the water around the back of the shaft. lining. At this stage, the shaft was a coal exploration venture and the water was not welcome.

Belton confirmed the depth at which the brickwork commenced and that they built it upwards for 18 yards (16.5 m). He gave the direction of the fissure of SE by E to NW by W (on a bearing 034°).

The Geological Survey's Lincoln Memoir (Usher *et.al*, 1888) gives an account of the Spa Bath Shaft, mentioning Granville, with an interpretation of the geology by Jukes-Browne (Table 1). The depth of 1,020 ft seems to originate from Skertchly (1877), who agrees with Granville on the depth of the spa water source, but published a total depth of 1,020 feet which was later conceded by Jukes-Brown to be a possible misprint for 1,200 feet (Well box 115/27). However, Jukes-Browne concluded that "the spring of saline water issued at a depth of 530 ft. and therefore appears to be in the Inferior Oolite" (*of which the Lincolnshire Limestone forms the main part*). The shaft was lined with brickwork to this depth.

	feet	m
Gravel and boulder clay	10	3
Kimmeridge and Oxford Clay	350	106
Kellaways Rock, blue clays, Cornbrash limestone, Great Oolite Clay and Limestone, Upper Estuarine	140	43
Lincolnshire Oolite and Northampton Sands	140	43
Lias, (Upper, Middle and Part of the Lower)	380	116
total	1020	311

Table 1. Geological log of the Woodhall Spa Bath Shaft by Usher *et al.* (1888).

These memoirs were written before the sinking of the other spa wells. With today's information on the deep geology of Lincolnshire, the rocks of the Woodhall Spa Bath Shaft might have been recorded differently. It is unfortunate that it is the Survey's conclusions that have been quoted in later publications.

When exploration for coal was abandoned, the flooded shaft became the spa water source. Flow rates were soon insufficient to satisfy demand for the developing Spa Baths, and storage tanks holding 156,640 gallons (712 m^3) were built to store water abstracted over the winter when the baths were closed. Some indication of original flow derives from the fact that Cheeseman and his colleagues were able to dig some distance below the fissure before they started to line the shaft and construct their conduit. It is possible that the water flow was a considerable nuisance near the limit of their pumping ability rather than the cause of any serious flooding, and they decided they had to solve the problem before digging deeper.

The deep adits

The inflow was measured in December 1886 at 1000 gallons per day (about 4500 litres per day, or less than a gently flowing tap), at the time when ways of increasing the flow were being discussed. This resulted in breaking through the brickwork built by Cheeseman and Belton and excavating adits (roughly horizontal tunnels) at the level of the supposed fissure (Well Box 115/27). Woodward (1904) mentions that the well "yealds 1100 gallons per hour", but this probably refers to abstraction rather than natural flow. Natural recharge after the adits had been partly excavated is estimated at about 1300 gallons (5910 l) per day, based on water levels during non-abstraction in February 1897.

It is these surveys concerning the depth and digging of the adits that supply most of the information on the actual geology of the well and the nature of the source rock. Drilling holes in the brickwork described by Cheeseman and Belton suggested that all the water came from rock situated between about 504 and 528 feet (154 - 161 m) from the surface (Hill, 1889).

By 1888 the initial adits had been dug with their ceilings at a depth of 520 ft (158.5 m), and their entrances cut through the cemented brickwork which Cheeseman stated extending down to about 540 ft (165 m). Earlier correspondence from Latham, one of the surveyors, had suggested that the

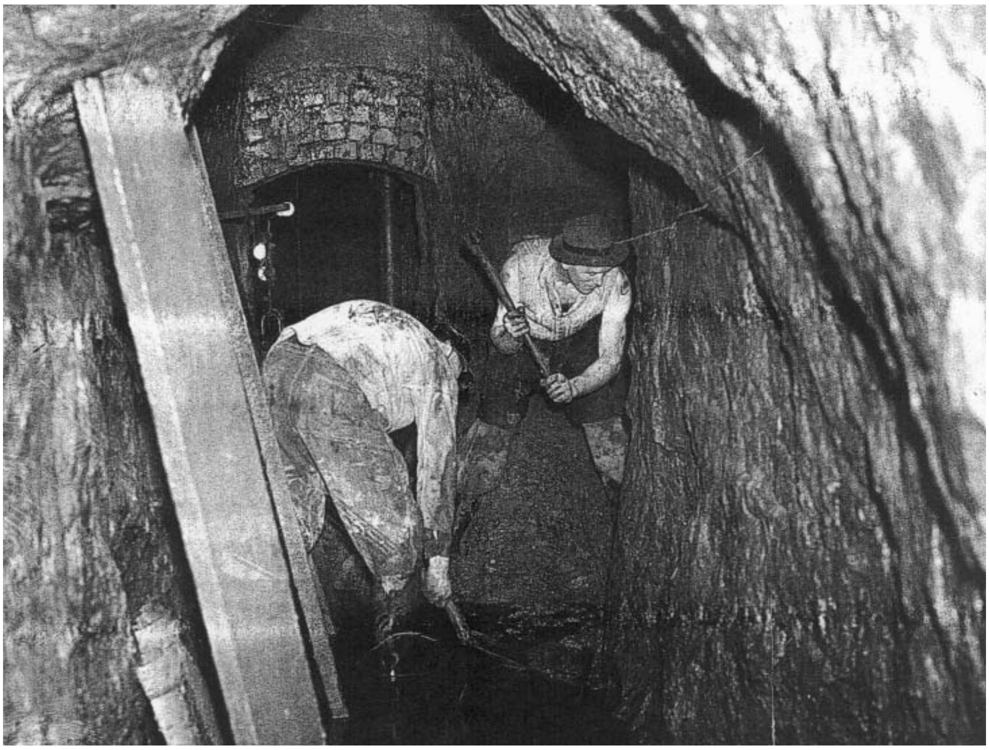


Figure 2. Clearing out the Spa Bath Shaft adits in the winter of 1952-3. (Woodhall Spa Cottage Museum)

source of the water was in the Kimmeridge Clay, but Whitaker, who wrote a report in 1898, probably with Jukes-Brown's survey in mind, suggested the Lincolnshire Limestone and associated beds formed the source. However, Whitaker was concerned with discrepancies between his observations and those of Jukes-Brown. After correspondence, Jukes-Brown admitted some amendments to his depths and thicknesses of the strata published in the Lincoln Memoir. Though his corrections complicate, rather than resolve, the situation they illustrate the difficulties experienced by these early surveyors.

Wilson (1899) surveyed the well in 1899 claiming to give the first accurate measurements of the shaft (Table 2). The adit entrances were 5 ft. 6 ins (1.7 m) high. Wilson also concluded from drilling 70 holes through the cemented brickwork that most of the water from the 'spring' entered the adits from between the floor of the northeast adit and 10 feet (3 m) above (presumably the adit top). He referred to only minor flows from the top and base of the underlying 7 ft. 11 ins. thick rock layer, but no water emanated from within that rock layer.

	feet	m
surface to the floor of the adits	506 ft 6 in	154.38
beneath which is		
cemented brickwork	10	3.05
rock	7 ft 11 in	2.41
un-cemented brickwork	20	6.10
rock**	24	7.32
alternating brickwork and rock to	750	229

Table 2. Log of the Woodhall Spa Bath Shaft by Wilson (1899). **His written report states 24 ft. for this layer, but his accompanying section shows the layer only 12 ft. thick.

This report gives the adit position as 19 feet (5.8 m) higher then that given by other surveyors. In 1889 Hill surveyed the depth of the Spa shaft as 786 ft, having measured the depth below the adits and adding it to Wilson's adit depth. Unfortunately the inconsistency between Wilson's plan and report must produce a question mark on these measurements. Adding 5.8 m to Hill's measurements gives 245.5 m, and natural infilling plus adit spoil could easily make up the rest of the shaft depth recorded by Granville (1841) of about 840 ft (256 m). The borehole drilled 120 yards (110 m) beneath that, would have been easily filled and not subsequently measured.

From 1889 to 1953 (Adit reports) extension and cleaning of the adits continued, in order to find more productive areas of flow and collect brine-rich mud, which was used in a hot poultice treatment called “fango”. The adits were easily excavated with pick and shovel, though there is the occasional reference to dynamite. The adit report of 1906/07 mentions that after tunnelling for 80 ft (24 m) along and upwards in a SSW direction they came up against a hard blue rock.

Many local people went down the well at the time of the last clearance in 1953, and John Sowerby reported (1992, pers. com.) that “the adits were roughly hewn out of the soft, grey, sandy rock, and there was a sizzling noise as the water slowly seeped in”. A photograph taken at this time (Fig. 2), shows

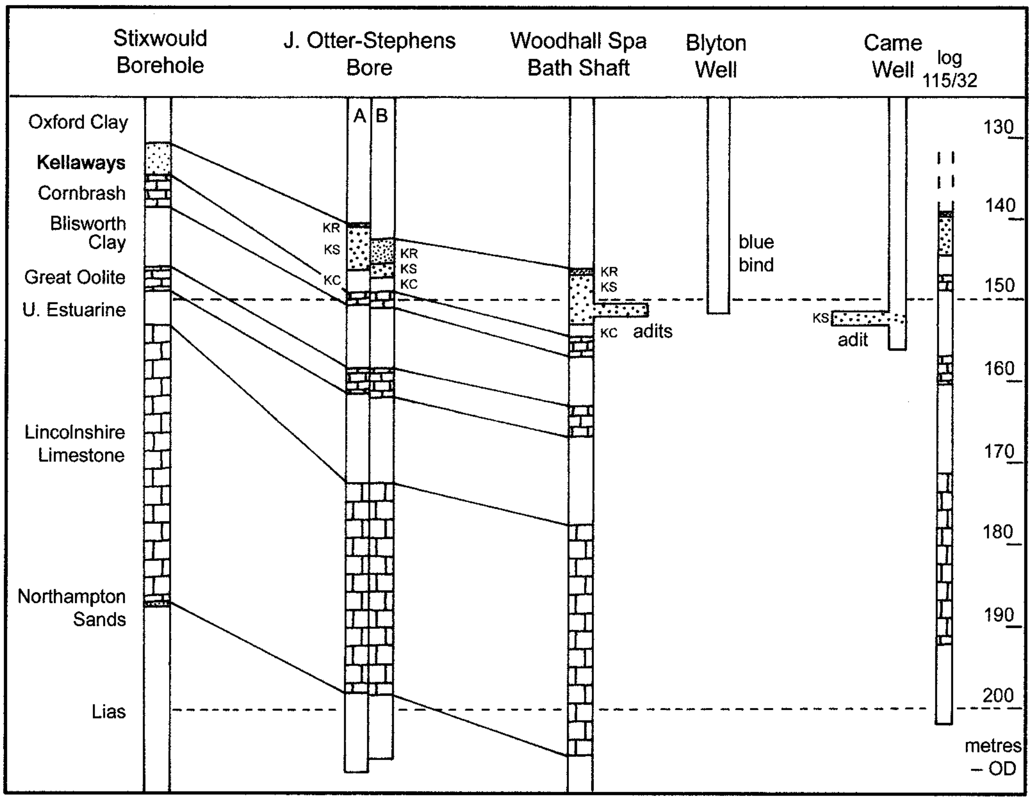


Figure 3. Logs of the boreholes and shafts around Woodhall Spa. The Kellaways may be divided into an upper rock unit (KR) above a sandstone (KS) above a clay (KC).

how the rock was easily working by pickaxe. This suggests that it is not in any limestone, including the Lincolnshire Limestone, of the Inferior Oolite, as indicated by Jukes-Brown.

The J. Otter-Stephens Bores

In 1897-98, J. Otter-Stephens, the secretary of the Woodhall Spa Company, commissioned a borehole to find an additional source of spa water. This bore was sited 300 m west of the Spa Bath Well (at NGR 191636, 4.9 m OD) (Well box 115/31).

Whitaker (Well box 115/27) commented that the rock samples extracted were reduced to a state of a sort of coarse sand. A log of the Otter-Stephens bore was published by Woodward (1904) and is shown as log A in Figure 3. A trickle of water was found at a depth of 490 ft. (149.3 m) in "a sandstone with iron pyrites" (Conway-Walter, 1905). This is most likely the horizon for the spa water, the higher level being accounted for by the regional dip.

A similar unpublished log (in the B.G.S. Well box), was prepared by Isler & Co., and dated 'about 1900' (log B in Fig. 3), but its location and datum are not recorded. Above the Upper Estuarine beds it gives depths slightly different to those in log A (Table 3), though below that they are nearly identical, suggesting that this is probably the same bore (Well box 115/31A). It appears that two shafts were sunk, because the first one was abandoned after the loss of the head gear when it was 91 m deep. This may explain the existence of two different but comparable logs (Well box 115/31). Whitaker's comments on the extracted rock samples suggest that measurement of the boundaries may not have been precise. Either log may be correct. Data on the Kellaways beds from log A fits better with the records from the Woodhall Spa Bath Shaft, and is therefore probably the more reliable.

Log A	ft. in		Log B	ft. in
Kellaways Rock	1 6		sandstone	9 0
sandy blue clay of Kellaways Sands	17 6		sandy blue clay	5 6
Kellaways Clay	6 6		Kellaways Clay	4 6

Table 3. The two logs of the J. Otter Stephens bores.

The Blyton Well

Woodward (1904) quotes a well log, his No. 4, described as "200 yards north of the Spa Hotel", also known as the Victoria Hotel and now demolished. Local legend suggests that this well was situated a few metres northeast of the Spa Baths, near the corner of Coal Pit Wood (close to NGR 195636; Fig. 1). The well was sunk by Mr Blyton, a local entrepreneur, in about 1877 (Conway-Walter, 1905) to create a rival to the Spa Baths.

It is recorded as 520 ft (158 m) deep, with the last 120 ft (37 m) described by Woodward as "blue blind, with beds of sandstone from 2 to 3 feet thick, and 12 to 14 ft apart", which he labelled as "Kellaways Beds, Cornbrash" etc. The position of the well close to the Spa Baths Shaft suggests that it might have reached the Kellaways beds, but most of the sandstone beds appear to be those in the lower part of the Oxford Clay, as in the Stixwould bore, or may be large nodules.

The Came Well

This well was dug (at NGR 195628, 8.2 m OD, Fig. 3) to supply spa water for R. A. Came's own spa at his Royal Hotel. It had reached 240 ft (73 m), when recorded by Woodward (1904), still within the Oxford Clay. On completion in 1905, adits were excavated with their roofs at 158.8 m depth. These were 1.8 m high, draining into a sump 2.7 m below.

The well yielded a good supply of spa water chemically similar to the Spa Baths, especially with respect to the iodine and bromine contents, suggesting it was from the same source (Table 4). The source rock was described by S. V. Hicks, the successor to the Came estate, as a “spongy sandstone, the yield slow, the water oozing out through layers of rock” (Well box 115/32). Conway-Walter (1905) recorded “water struck in soft spongy stone at 492 feet” (150 m), but gives shallower depths than Hicks for the other measurements. Conway-Walter used second-hand information, while Hicks, as the trustee of the Came estate, could refer to the well sinkers’ records. Hicks’ information should be more reliable. A sample of rock supposedly from this aquifer, examined by the Geological Survey in 1934, was recorded by “C.W.” as “bluish crumbly sandstone with a belemnite” and “certainly Kellaways sandstone” (Well box 115/32).

These depths in the Came Well suggests that the adits were probably cut at the base of the Kellaways Sand, slightly below the level of the Spa Bath Well adits (which were cut first by trial and error), possibly to obtain the maximum drainage from the source rock. The adits are probably floored by the Kellaways Clay, with the sump in the Kellaways Clay, though water may have been lost if this had entered the Cornbrash, as its depth could imply, and was not subsequently backfilled.

Among the data for this well is a copy of a log titled ‘Woodhall Spa’, which has the Geological Survey reference number 115/32, the same as that used by the Survey for the Came Well. This was found in a series of papers given to the Woodhall Spa Cottage Museum archives in 1999. It cites the same location as the Came well, but at an altitude of only 6 m, while the Came well is at 8.2 m. This log is included on Figure 3 for comparison, but it is difficult to reconcile it with other data, and it must be considered suspect.

The Stixwould Borehole

In 1944, the D'Arcy Exploration Company drilled a series of boreholes in the hope of finding exploitable reserves of oil. These included the Stixwould Well No. 1 (at NGR 188653, 7.6 m OD, Fig. 1). The upper part of this log is included in Figure 3.

Swinnerton and Kent (1976) record different depths in the Stixwould borehole. They quote about 200 feet for the Amphill Clay, while the D’Arcy log shows 166 ft for this and possible the Kimmeridgian. They cite 249 ft for the Oxford Clay while the log shows 261 ft, and they have 21 ft of Kellaways beds while the log records only 13 ft. They also commented on the regular development of the Kellaways beds throughout Lincolnshire, where they are rarely less then 25 ft or more than 35 ft thick (Swinnerton and Kent, 1949). Kent would certainly have known about the Stixwould bore since he worked for D'Arcy Exploration, who sunk the well, and data on the Jurassic rocks in the boreholes was published by Lees and Taitt (1946).

The figures from Swinnerton and Kent (1949) make the depth to the Kellaways about 478 ft (146 m), when surface gravels are included, rather then the 456 ft (139 m) given in the D'Arcy log. The lower depths would fit better with data from the other wells, but the Stixwould bore is further from the others, so differences may be due to undulation and bed thickness variations. The regional dip is about 1 in 75 almost due east.

The borehole record was based on mud samples and drilling rates only, since electric logging was not then in use (Field, 1989). We might speculate that Kent had had access to unpublished information in 1949, but his sources are not recorded. The data in Figure 3 is therefore based on the D’Arcy well log.

Geology of the Woodhall Spa Bath Shaft

A best assessment, based on evaluation of the various records, of the geological sequence within the Spa Baths Well is shown in Figure 4.

Measurements of the rock and brickwork by Wilson (1899) correlate better with the other borehole data when added to Whitaker’s adit depth measurement of 520 ft (158.5 m). His 7 ft 11 ins (2.4 m) of exposed rock beneath the cemented brickwork, is then most likely to be the Cornbrash. The 20 ft (6 m) of uncemented brickwork beneath passes through the Great Oolite (Blisworth) Clay, and the rock layer below is the Great Oolite Limestone. This suggests that the thickness of 12 ft shown on Wilson's sketch is correct, and not the 24 feet given in his report. Wilson's measurements for the thinner beds are probably more reliable, since these would be easier to measure than the full depth.

The reference by Belton and Cheeseman (1839) to encasing ‘18 yards of soft spongy rock’, within the Spa Bath Shaft, has often been interpreted as referring to a thicker rock (such as the Upper Estuarine Series between the Great Oolite and the Lincolnshire Limestone), or as a misprint for

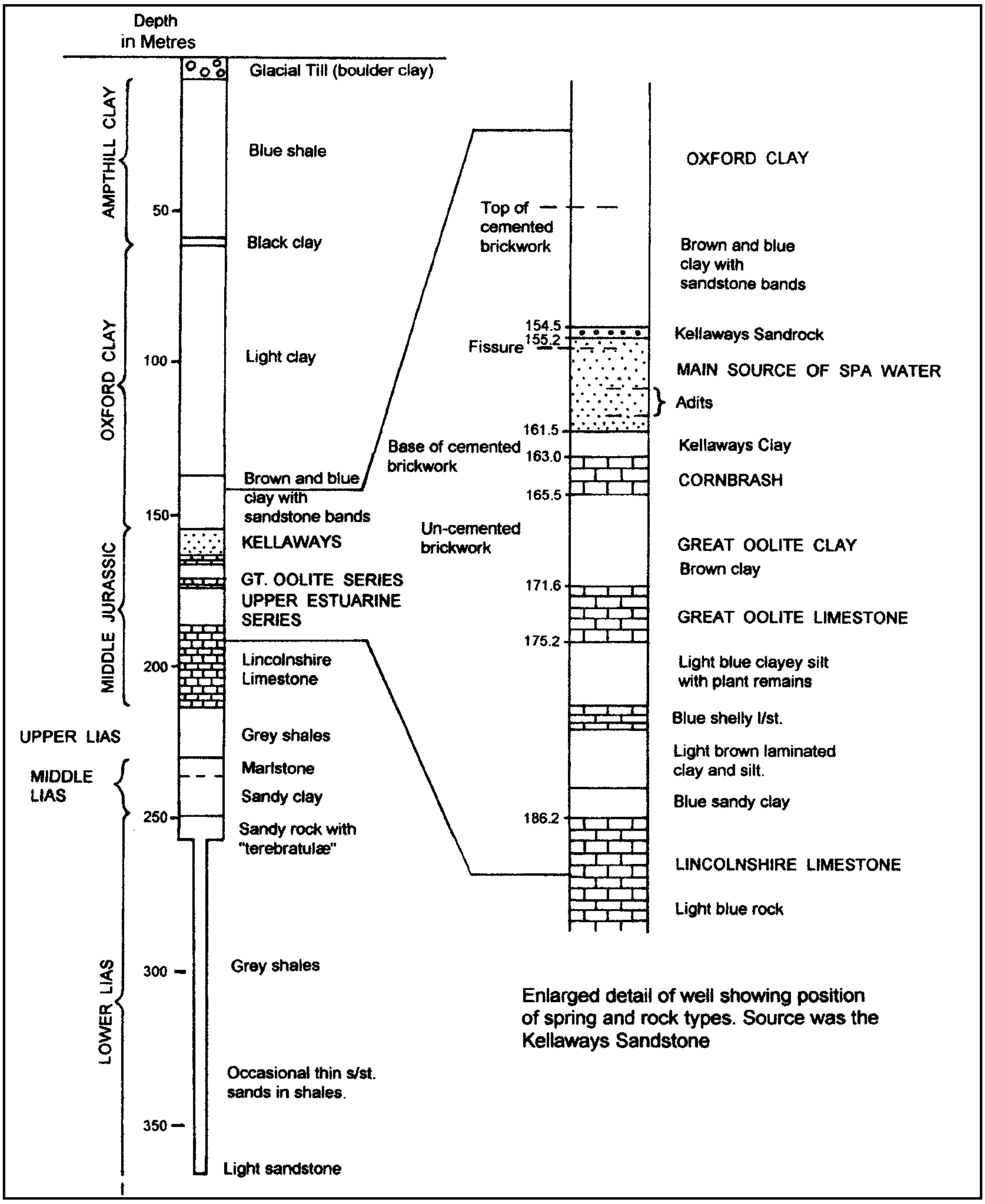


Figure 4. Geological log of the Woodhall Spa Bath Shaft. The narrow lower part is the bored hole, while the upper part is the excavated shaft 2.4 m in diameter.

Granville's ‘18 feet’, despite the clarity of the handwritten statements. It is likely that this refers to the lining through more than one bed. The well sinkers would not have worked higher than necessary, but would have sealed anything that was producing a flow. This could include silty sandstones within the lower Oxford Clay, as described in the Stixwould and Blyton bores. The well sinkers worked upwards with speed and probably in poor light to prevent further flooding, and started from the solid ledge afforded by the Cornbrash, thus also encasing the Kellaways Clay. This is more logical then lining through hard limestone such as the Cornbrash, which Wilson states only yielded a minimal flow of water. If the Cornbrash was covered within the 18 yards of cemented brickwork, it would probably have been remembered and described as a distinct interruption to the normal friability of the source rock, that is mentioned in their accounts.

The water noted by Wilson (1899) entering from up to 10 feet (3 m) above the adits in the Spa Baths Shaft suggests that the aquifer extends upwards to at least that level. This confirms Granville's description (1841) that the source was about 170 yards (155 m) deep, and the hard blue rock encountered when digging the adits in 1906/7 was probably the Kellaways Rock. This would allow a thickness of about 6 m for the Kellaways Sand as the source rock, with 1.5 m of Kellaways Clay beneath, above the Cornbrash exposed beneath the cemented brickwork. Granville's thickness of 17 to 18 feet

(5.2-5.5 m) for his source rock is a reasonable approximation to this, in view of the fact that he obtained the data from men employed to fix the pipes to pump up the water and not by direct measurement. Granville discusses only the source of the 'spring' (1841), and not other beds that might occur behind the cemented lining.

It would appear that Granville's description is essentially correct,and the source rock for the spa water was the Kellaways Sands. In Figure 4, the depths to beds beneath the Lincolnshire Limestone are taken from the Stixwould bore.

The source of the spa water

A number of analyses of spa water are quoted in the literature. Pre-1920 analyses are reported as a hypothetical mixture of salts which, if dissolved in water, would produced the observed chemistry. Such presentation is completely artificial, and the analyses have been recalculated as individual ions, and presented in Table 4. Most refer to the Spa Bath Shaft, but there is one analysis of water from the Came Well. The analysis quoted by Edmunds et al (1969) appears be of a sample collected in 1953 when the Spa Bath Shaft was last cleaned out.

All the spa water analyses show elevated concentrations of iodine and bromine. A comparison with the composition of average seawater (Table 5) shows that Na/Cl and Br/Cl ratios are close to those of seawater, whereas there is an iodine enrichment of two orders of magnitude in the spa groundwater. Although the high bromine content is probably a reflection of the high salinity of these groundwaters, possibly derived from mixing with old formation waters within the Kellaways Sand, the high iodine concentrations cannot be explained by simple mixing. Iodine enrichments relative to seawater are not uncommon in British aquifers and both the Chalk and the Lincolnshire Limestone have enhanced iodine concentrations. The source of iodine is thought to be associated with the breakdown of marine-derived organic matter (Edmunds et al, 1989).

chemical ratio	Na/Cl	Br/Cl	I/Cl
Spa Bath Shaft water	0.51	0.0035	0.00042
Seawater	0.55	0.0034	0.000003

Table 5. Comparison of the Spa Bath Shaft water with seawater. Average values of 7200 Na, 14000, Cl, 5.9 I and 50 mg/l Br have been used, against the values for average seawater given in Table 4.

The composition of groundwater from the Came Well differs slightly from that of the Spa Bath Shaft. Although bromine and iodine concentrations are still high, the overall salinity is reduced, and calcium and sulphate concentrations are higher. It has already been suggested that the Came Well adits were cut slightly below the Spa Bath Shaft adits at the base of the Kellaways Sand, and the chemical differences may reflect mixing with groundwaters of slightly different composition. Iodine occurs mainly as iodate (IO3) in oxidising groundwaters. The presence of ammonia and dissolved iron in some of the analyses, and the faint smell of H2S reported in the Lincoln memoir (Usher *et al*, 1888), suggest that these waters are reduced, and that iodine will be present as iodide.

Acknowledgements

The author is grateful to the British Geological Survey for access to well logs and notes from their various well

source	WSBS	WSBS	WSBS	WSBS	Came Well	WSBS	WSBS	seawater
analyst	Frankland	Wright	Wanklyn	Frankland	Trotman	Thorpe	?	average
date	1874	1883	1886	1891	1908	1911	1953	
reference	Skertchley	Ussher	Woodward	Woodward	Luke	Luke	Edmunds	
Na		6 089	6 907	7 693	5 712	7 245		10 500
K		46		9		28		380
Ca		549	571	555	1 285	544		400
Mg		280	329	301	230	156		1 350
CO_3		68	86	116	135			
Cl	14 250	11 114	14 141	13 514	11 569	14 246		19 000
SO_4		112	3	79	1 857	68		2 700
I	8.8	5.2	5.6	5.7	12.0	5.9	6.0	0.06
Br	63	50	49	47	57	34	38	65
SiO_2		2.6		8.5	28.0	9.8		6.4
iron etc		1.3	tr	2.9	19.0	5.3		0.1
NH_3	8.1	6.0		9.4				
tds	23 612	20 200		22 624	20 851	22 325		

Table 4. Analyses of the Woodhall Spa water. All figures are given as mg/l; tds = total dissolved solids; tr = trace; WSBS = Woodhall Spa Bath Shaft.

boxes and for helpful advice, to Prof. John Mather for advice on the water chemistry, to B. Osbourne for the Came Well water analysis, to John Sowerby and G. Overton for local information, to David Robinson for advice and data from his personal reference collection, and to Woodhall Spa Cottage Museum for access to unpublished research material.

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Michael Czajkowski,
96 Tor O Moor Road,
Woodhall Spa LN10 6SB.

Nottingham Trent Geohazards Group Professorial Lectures

Edited by Mike Rosenbaum

The delivery of an Inaugural Lecture by a newly appointed incumbent is a long standing tradition for those awarded a Chair in a British university. Nottingham Trent has upheld this tradition through its Professorial Lecture series, publishing those delivered in the period 1989-1996 as a compendium entitled ‘Thinkers and Shapers in the Modern University’ (Watson, 1997).

There has never been a Geology Department as such in the University or its predecessors. Nevertheless interest in the ground has been encouraged, particularly the issues facing the built environment. The ground-related research has been led by the Geohazards Group. This has helped maintain a vibrant and active research culture, enhancing the University’s distinctiveness and quality through the appointment of professors, four of whom have joined in the past three years. Each has delivered an Inaugural Lecture, so providing an insight to the range of geohazards that affect our society - Mike Rosenbaum on 24th May 1999, Ian Smalley on 11th October 1999, Martin Culshaw on 30th January 2001 and David Butcher on 1st March 2001.

The Geohazards Group

Geohazards are a danger, or source of danger, arising from the ground conditions. They may be a danger to mankind, may damage the environment or may cause excessive cost and disruption. They may cause ground failure, often precipitated by human activity. Their study requires expertise in the key areas of geotechnical engineering, engineering geology, hydrogeology, risk management and planning. The Geohazards Group at the Nottingham Trent University is investigating the reactions of the ground to natural and manmade processes, and their engineering implications relating the outcomes to the user community. In most instances these require attention to be concentrated on near surface processes rather than on the deep rock profile. This involves quantification of the processes rather than classification of their products.

Four foci of activity have developed within the Geohazards Group:

a. Ground Engineering - investigating new technologies appropriate to sustainable development and remediation strategies for earthworks, slope instability and foundation engineering.

b. Ground Investigation - developing the identification of geohazards and assessment of their impact on land value, residential development and use of derelict land, and developing spatial analysis techniques and decision support systems appropriate to the evaluation of ground performance in the built environment.

c. Geo-environmental Management - furthering our understanding of the natural environment with particular emphasis upon the management of current issues, notably wetland restoration, pollution travel times, reservoir sedimentation and sediment controls on catchments.

d. Public Policy and Awareness - raising professional consciousness and developing a general public awareness of ground engineering science in relation to the built environment, dealing with social applications and the outcomes for society, and thus with policy. The focus is investigating how the ground has been recognised and depicted through history, in the geological map, and how ground has been perceived through statutory processes.

The Geohazards Group has its own web site at: construction.ntu.ac.uk/graduate_school/Research

Professor Mike Rosenbaum -
The ground beneath our feet: geohazards in the built environment

Geologically active processes, leading to volcanism and rapid crustal movement, have obvious consequences for those who live in the vicinity, but such a model enables the geologically-related hazards to be recognised and the consequent risks assessed across the globe. Remote from a modern plate boundary, the heat and stress effects of former zones of plate collision have become locked into the rock fabric. With unloading and reduction of temperature, rock materials become brittle, and with loss of confinement they expand leading to cracking, effects exaggerated by ice. Man’s activities can change the rock condition still further. Conceptual models are developed to help our understanding of how the ground might influence site behaviour.

Geohazards are adverse events arising from processes acting within the ground. Causes are of scientific interest, but it is the consequences which are of greatest concern to the public. Current attitudes for dealing with hazards are discussed in the context of dealing with consequence as well as dealing with cause. The properties of the geological profile and the processes operating within it determine where and when an adverse combination of circumstances might become linked together, quite possibly induced by human action, so bringing about an imbalance that triggers failure. Taking into account the likelihood of geohazards occurring, together with an assessment of the vulnerability of people, property and environment in the vicinity, provides support for decisions as to what should be done to mitigate the consequences. As important is the need to enhance public perception, increasing education, awareness and information.

Man's activities must next be considered alongside natural geological processes to investigate whether these might change the stress state still further. Additional energy release will lead to rebound, cracking and ravelling. But how much will occur, and how deep will it extend? The ground can, and has been, changed for the benefit of Man: changing the shape of the surface, decreasing settlement by reaching down to less compressible layers, or increasing the ground's ability to carry load by spreading the foundations or taking them deeper. Around Nottingham there are the consequences of mining in rock, from coal, gypsum, limestone and sandstone, the 'caves' in the latter having been comprehensively described by Tony Waltham (1996), with direct effects on the built environment. Water exerts an important influence, weakening the rock in the roof, walls and pillars.

There are weak rocks elsewhere too, such as the Chalk, a soluble rock that develops karst,along with its natural cavities, and also contains mines, which are often forgotten over time. An example is from Pinner in North London. This mine was only detected when a depression developed in a footpath, but clues as to the presence of a former mine were in the form of chalk fill on terrain where chalk does not outcrop at the surface, and the occurrence of London & Birmingham Railway sleepers indicating a very old rail link to the former workings. Such cavities can have seriuosly adverse affects on the built environment, as on the reduced load bearing capacity of piles driven into a similar old mine in Norwich (Fig. 1).

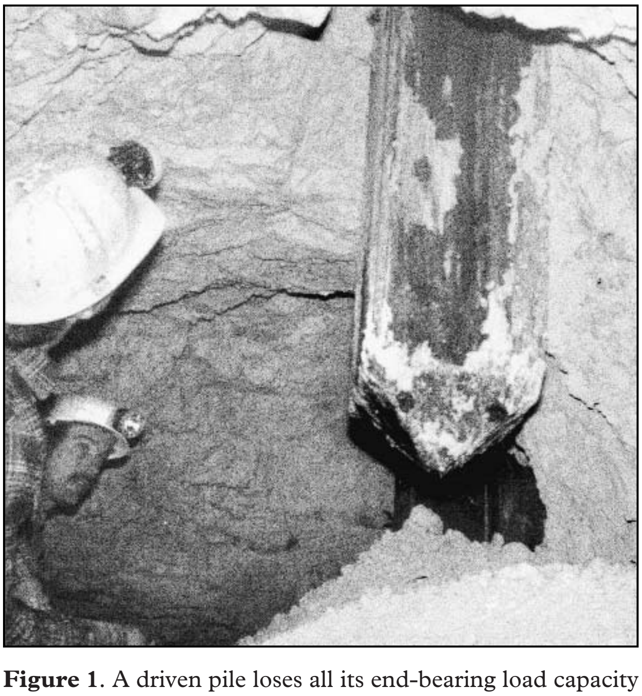

Figure 1. A driven pile loses all its end-bearing load capacity when it breaks through the roof of an old chalk mine in Norwich.

The ground is significantly affected by the climate. The first lectures as to how geology influences engineering behaviour were given by Herbert Lapworth at Imperial College, whose similar presentations to the Institution of Civil Engineers were later published. However, the relationship between geology and engineering was already well established, notably helped by William Smith, the canal engineer who produced the first comprehensive map of the geology of England and Wales in 1815, giving a framework for understanding the likely ground conditions at any given location.

The climate not only physically alters the rock but chemically alters it too, leading to weathering, the importance of which is to progressively rot the ground from exposed surfaces (from the ground surface itself or from the surfaces of fractures), thereby weakening the ground. However, these processes also enable new substances to grow, even in contact with artificial materials such as the growth of silica gel as the result of alkali silica reaction concrete between aggregate and cement which has even led to building collapse.

The keys to tackling ground-related hazards lie with understanding the processes, and effectively communicating their consequences. The processes may be considered in terms of those that occur naturally and those that are due to the influence of Man. The natural geological processes may be considered in terms of:

- active processes, that could make the ground unstable
- dormant processes, that might be re-activated (notably those active during the Quaternary)
- fossil processes, which have left the ground in an unstable condition.

The natural geological processes of greatest concern to engineering are essentially those that are active or have been active during the Quaternary. Processes respond to change, leading to reactions to restore a state of equilibrium. Most engineering works in the built environment thus need to incorporate a consideration of the geological profile, tempered with anthropogenic stratigraphy and identification of active processes, to fully appreciate the potential geohazards.

Biographical Note

Professor Rosenbaum has been involved with engineering geology for most of his career. Having studied at Imperial College, he started work at Soil Mechanics Ltd (first in Site Investigation and then in the Foundations Division), learning on site about how engineering is influenced by the ground, including a spirited discussion about whether or not solifluction had affected a 7° hillslope in London Clay – this started to move when the new motorway was being constructed, conclusively proving the point! He then returned to Imperial College, to pursue research for his PhD concerning the 'laboratory simulation of burial diagenesis of sediments', before taking up an academic appointment in engineering geology, still at Imperial College. Mike Rosenbaum is now Professor in Geological Engineering at the Nottingham Trent University and Head of the Geohazards Group.

Professor Ian Smalley - Loess: the yellow earth

What have the following in common: Buckingham Palace; the collapse of the Teton Dam in Idaho in 1976; the origins of the Chinese civilisation; the 'dustbowl' of the 1930s in middle America; the economy of New Zealand; and the great 1920 earthquake in Gansu Province, China? The common factor is loess, a yellow soil or sediment that is essentially silt sized (20-60 µm) and deposited by the wind. It used to be said that everybody who had survived a high school geography course knew three things about loess: it was yellow, it was deposited by the wind and it was found in China (Fig. 2).

Loess grows good crops (Iowa is virtually covered in loess) and makes good bricks. Buckingham Palace is made of bricks from the loess deposits in North Kent. The locals call it brickearth, but it is true loess. The 90 m high Teton Dam in Idaho was made of loess, which is not good dam construction material, and the dam failed as the reservoir was being filled. The Chinese civilisation, the only one of the ancient civilisations to survive until today, developed in the loess lands of northern China. Loess suits simple agriculture, and 4000 years ago the loess lands were wetter than now and grew good crops. The loess, having blown into position, can blow away again and this is what happened across the Mid-West USA in the 1930s. Desperately dry conditions and less than perfect farming practices allowed the surface of some of the valuable land to blow away; luckily much remained, as a major national resource. New Zealand has loess and rain in abundance, and as a result it grows sheep and grapes and trees and survives in a difficult trading world. The great 1920 earthquake in Gansu mobilised the loess ground into huge flowslide movements; the total area in motion was about the size of Ireland. Many thousands of people, who lived in the easily excavated caves in the loess, were killed. In terms of loss of life, it was the worst natural disaster ever to occur.

We need to look at two beginnings of the loess story, an ancient beginning and a comparatively recent beginning. The ancient Chinese were well aware of the loess and its remarkable properties. They observed the Yellow River with its huge suspended load of loessic material (about 40% solids), and noted the vertical features and cemented nature of the material. The Yellow Earth (huang ta) was important, and indeed yellow became the Imperial colour. But there is no record of ancient landform science; the Chinese were astronomers and engineers, but not, apparently, geomorphologists. The poets took note of the material. In the Imperial capital at Chang-an, the Tang poets of the 8th century wrote often of dust, which was everywhere.

The recent beginning takes place in Heidelberg, around 1830. Karl Caesar von Leonhard named the material Loess. This was a great scientific leap; once the material was named, its nature, and mode of formation, could be investigated. An interesting coincidence occurred at this point: Charles Lyell, who was then engaged in writing one of the seminal works in the earth sciences The Principles of Geology, set out for a honeymoon trip down the Rhine. He met von Leonhard in Heidelberg, was shown the loess, and was so impressed by it that he included a loess section in Volume 3 of the Principles. The Lyell book proved to be a huge success and its wide distribution meant that news of loess spread around the world. The 'loess problem' for 19th century scholars was 'how was the material deposited' and a range of opinions was proffered.

By 1880, a theory of loess deposition was well in place. Baron Ferdinand von Richthofen had successfully promoted the idea that loess material was transported by aeolian mechanisms, i.e. that the wind blew the loess into place. This theory was soon widely accepted, particularly in North America.

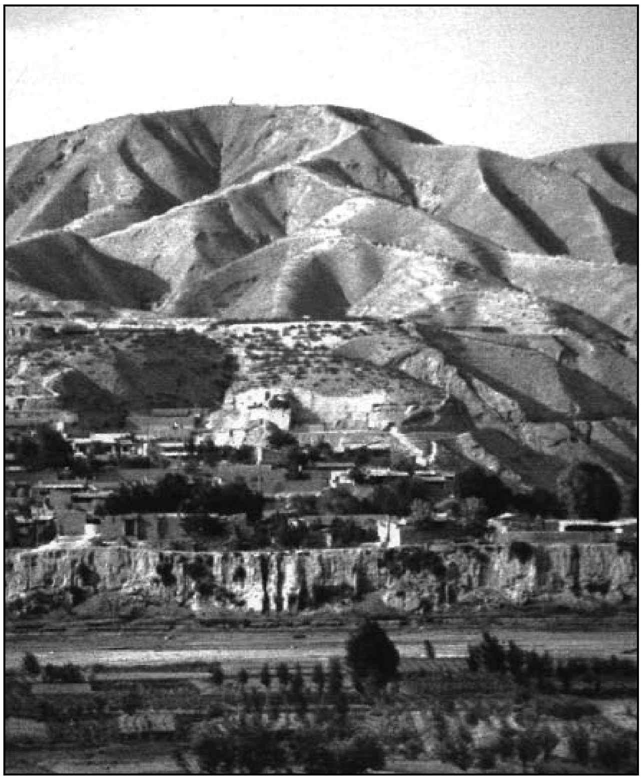

Figure 2. Gullied slopes in thick loess in the Yellow River basin near Lanzhou, central China.

There is only one major maverick diversion that needs to be identified: L.S. Berg, in the early days of the Soviet Union, promoted the idea that loess formed in situ by a sort of 'loessification' process. He especially denied any validity to the aeolian hypothesis. The Berg hypothesis can now be seen to derive directly from the basic soil forming ideas formulated by V.V. Dokuchaev in the late 19th century. The in situ theory was a truly Russian theory, and in the chauvinistic days of the early Soviet state was inevitably accepted. As might be expected in the hierarchical structure of Soviet science, a theory, once accepted, became very difficult to adjust and correct. The Berg theory, operating between about 1920 and 1960, was echoed by R.J. Russell in Louisiana in the mid-1940s, but he was probably the only influential western supporter.

Today we recognise that those particles in finer-grained detrital sediments are usually composed of quartz. Most particles fall into two size grades: sand (2 mm-62 μm) and silt (62 μm-2 μm). These size gradings conceal important processes, since there are geological controls on both the sand and the silt populations of quartz.

Sand nature is largely controlled by geochemical reactions, for example in cooling granite from which it is eventually released by weathering action. The quartz is among the last part of the rock system to solidify and the eutectic-like reaction which occurs ensures that the quartz exists as small crystalline units, each suffering cooling and recrystallisation stresses on a significant scale.

Silt production

Silt is broken quartz, and has traditionally been considered to lack a specific geological control. The situation is confused by the large range of materials that fall into the size category, but there do seem to be distinguishable modes and possibly comminution limits within the 60 μm span. The controls operating in this size range are probably the critical concentration of 'Moss defects' in the quartz particles. Moss postulated the formation of specific crystal defects in the quartz that formed in granites. These affect sand formation, and it is possible that they also control the modal size of silt particles. Within the silt range there may be several usefully definable populations, as Moss proposed for sand. The Quaternary appears to be a silt-rich period due to tectonic and glacial activity, but silt production is apparent throughout the sedimentary record. Very long-term silt producing processes are required.

To produce silt in nature on a large scale, very energetic processes are required. Many processes that are believed to generate silt particles have been listed. However, large-scale production is essentially due to glacial grinding, or to intense weathering processes in high, cold, tectonically active mountain regions. The heart of High Asia is a major generator of silt particles. These form the productive alluvial soils of northern India, most of Bangladesh, the loess deposits of the Syr-darya and Amu-darya rivers in Central Asia, and the great loess deposits of North China. Some claims have been made for silt production in hot deserts. Large amounts of very fine aerosolic dust are produced, but in terms of loess-sized particles this is a small-scale process and leads to modest, disputed deposits. The loess deposits around the Sahara usually have smaller mode sizes (in Nigeria) or larger mode sizes (in Libya and Tunisia) than the true Chinese mode at 25 μm.

The silt particles were formed by late Tertiary and Quaternary processes, and reflect the expenditure of a considerable amount of geo-energy. Deposits of loess underlie much of the most productive agricultural land in the world, and suffer the worst erosion problems. Silt also presents a series of conventional geotechnical problems. For example, it has the ability to form very open, metastable structures that collapse when loaded and wetted, thus causing continued foundation problems. The steep slopes in the loess of northwestern China are vulnerable to landslide failure, and these slides may become very destructive flowslides, resulting in large loss of life and infrastructure. The Teton dam, on the Teton River, above Rexburg, Idaho, failed in 1976 largely because it was built of silt, a material not well understood by engineers. Sowers (1993) has described the Teton Dam collapse as the worst civil engineering construction failure of the 20th century, not because it did vast damage or caused large loss of life (it did not) but because of the loss of confidence it caused in the civil engineering profession (Fig. 3).

Loess consists essentially of silt-sized (typically 20-30 μm) primary quartz particles that form as a result of high energy earth-surface processes such as glacial grinding or cold climate weathering. These particles are transported from their source by great rivers - notably from the tectonically active mountains of the Himalayan and Alpine ranges by the Huang He, Danube and Rhine. Subsequent flooding of these rivers allows the quartz silt particles to be deposited on flood plains. On drying out, these particles are detached and transported by the prevailing winds until deposition leeward at distances ranging from tens to thousands of kilometres. This process has resulted in the almost continuous deposit of loess from the North China plain to southeastern England. The major loess deposits underlie highly populated areas and major infrastructure links, and are prone to collapse and ground subsidence. The areas of most widespread concern are concentrated in Eastern Europe and Russia and to a growing extent in China (Derbyshire *et al.* 1995a), although serious problems of potential collapse exist wherever loess is found.

Figure 3. Failure of the Teton Falls Dam in Idaho, USA. The face of the loess dam is on the right, with the rock canyon wall on the left. The core of the dam has just totally collapsed into the piping cavity that had progressively enlarged along the original line of seepage through the permeable loess. (With thanks to the unknown photographer)

Metastability and subsidence

The particles that make up loess, although principally of quartz, consist also of feldspars and micas. Clay-sized particles within the loess structure consist of quartz, feldspar, carbonates and some true clay minerals. This compositional picture is complicated further by differences in (particularly the mineralogy of) the clay-sized fraction in loess and palaeosols, both between different climatic regions and between loess units and buried palaeosol horizons within the same climate environment. These differences are a fundamental cause of variation in metastability, and hence the potential collapse that may result after a loess soil is loaded and/or wetted. In addition, the primary quartz particles are irregular in shape (Rogers and Smalley, 1993). As a result of their genesis and constitution, loess deposits form remarkably open structures with the interstitial clay-sized particles congregating at the quartz particle contacts. This open structure is maintained by a process of bonding, the strength of which increases with time.

Natural loess typically has an open structure with a voids ratio of 0.8-1.0 or more, and is found in three main forms: sandy-, silty- or clayey- loess. The primary quartz particles are held in this condition by bonding, the nature of which is variously attributed by researchers world-wide. It has been shown (Jefferson and Smalley 1995) that loess has a bond-weight ratio of approximately unity, making the bonding a crucial element of natural loess behaviour.

Bonds break down progressively as increased stresses are applied at the natural water content, but more importantly the structure undergoes immediate and considerable collapse (up to about 15%) if saturated. The structure is therefore metastable in its natural condition. Such collapse has resulted in catastrophic failures that, in some cases, have caused considerable loss of life.

Although this bonding can maintain a relatively open (i.e. high voids ratio) structure underneath considerable thicknesses of overburden (e.g. the upper 10 to 38 m Malan loess of the 400 m thick sequence in China), it is still metastable and the structure will collapse under conditions of additional loading and/or wetting (Derbyshire *et al.* 1995b). It is this metastability that results in the most widespread and costly problem of engineering geology of loess: hydroconsolidation subsidence. The impacts of this process are enormous on infrastructure, urban and rural developments in China (which is the fastest growing construction market in the world) and Eastern Europe, and pose considerable problems in all other countries where loess is found. In one small district of Lanzhou in China, 101 out of the 168 buildings have been damaged or destroyed as result of loess hydroconsolidation in the last 10 years. In Britain, engineers face this problem on the loess up to 8 m thick in Essex and on similar deposits elsewhere in the south of England (Dibben *et al.* 1998).

Clearly, a treatment process is required that can safeguard any structures built on these deposits - which include possible radioactive waste repositories constructed in the loess of northern Bulgaria. Before a safe, effective and economical technique can be established, it is vital that the mechanisms of loess metastablity and subsequent collapse potential are fully understood.

Biographical Note

Professor Smalley took his PhD at City University, London, on packing and cohesion in particulate sediments and soils, whilst a lecturer in chemistry. He subsequently held academic posts at Leeds, Leicester and Loughborough, at City University of New York in the USA and at the University of Waterloo in Canada, and for 5 years was a research scientist at the New Zealand Soil

Bureau. He has held numerous senior posts in national and international learned societies, and is currently President of the INQUA Loess Commission. Perhaps Ian's most famous contribution to our understanding of the ground has been his realisation (reported in Nature in the mid 1960s) that Britain was sinking in the southeast, but rising in the northwest, due to isostatic recovery following the melting of the great Pleistocene ice sheets. Ian Smalley is now Visiting Professor in Quaternary Engineering Geomorphology at the Nottingham Trent University.

Professor Martin Culshaw - From dig-it-all to digital: the rise and fall and rise again of the geological map

Topographic maps provide a scaled-down *representation* of (usually) part of the earth's surface whereas the geological map is an *interpretation* of what is in the Earth. The lecture described how geological maps were first produced to help the exploitation of minerals and assist engineers in construction. However, once Geological Surveys began systematic national geological mapping and geology became an academic subject in our universities, the practical origins of the geological map were somewhat forgotten. For almost 150 years geological maps were interpretations by geologists, for geologists. Only in the last 30 years, or so, have geological maps begun to return to their practical roots. This period has seen an explosion in the types of geological maps produced and the range of users. The increased power of desktop computers and the continuing development of software that allows map data to be manipulated are now accelerating this process. Examples of some of the new digital maps that provide information for a variety of uses were presented using the *MapInfo* software on a laptop PC.

Geological maps were created for essentially practical purposes but then became, to some extent, an end in themselves. Only as the user became more demanding, in the latter part of the 20th century, did the geological map return to its applied beginnings. With the rapid development of digital technology, the geological map is now on the verge of a new golden age that will reach into the lives of everyone.

A map is like a portrait - it provides a representation of something, the accuracy of which depends on the skill, and the intention, of the creator. Like a portrait, the map can be at a variety of scales, in a variety of styles, and in full colour or in monochrome. Maps of the Earth's surface (topographic maps) are those with which we are most familiar - where the information to create them is almost wholly observable, and the position of each point on the Earth's surface can be measured relative to any other point.

The geological map is different. Unlike a topographic map, which is a scaled down representation of a part of the Earth's surface, the geological map is a two dimensional representation of a three dimensional object - the ground beneath the surface. Furthermore, only a tiny amount of the subsurface is observable by the geological mapmaker. Consequently, the map is not a representation, but an interpretation of what is in the ground.

The study of the Earth has many aspects to it. Some geologists look at the composition of rocks (petrologists and mineralogists), some are concerned to understand the way life has evolved through examination of the fossil record (palaeontologists), while others seek to classify the rocks in terms of their age and how they came to be where they are today (stratigraphers). It could be argued that these geologists are mainly interested in geology for its own sake, and are less concerned with whether what they do has any practical application. Their work is often described as pure geology, in the sense that it is not influenced by considerations other than the pursuit of knowledge.

Geohazard mapping

Other geologists are more concerned with the relevance of geology to improving people's lives. Such scientists are usually referred to as *applied* geologists. Unfortunately, some 'pure' geologists also see them as being the opposite of pure, by implication being partial, insincere, shallow and corrupted by all the usual influences of society. There may also be the implication that they are somehow less worthy than 'pure' geologists; to put it more simply, they are second-rate!

However, while it is clear that geology is of key importance in wealth creation, it is also very relevant to the improvement of the quality of life. The industrial revolution, which the availability of geological materials helped to fuel, also produced an environmental legacy with which we are only just starting to come to terms. As we move into an era in which future development will have to be increasingly sustainable, so geologists are having to provide society with the information needed to achieve this. Society needs to be assured that our groundwater is safe to drink, that our buildings and infrastructure are safely constructed, that the ground that we use for building, recreation and cultivation is not contaminated and that we do not exacerbate natural geological hazards.

The geological map was a major tool in assisting geologists in the discovery of mineral resources. In Britain, where we have exhausted many of these minerals, the use of the geological map for this purpose has declined. However, our increasing environmental concerns are giving a new impetus to the need to record and present geological information.

Geohazard maps for the insurance industry provide an illustration of the applicability of the geological map. The late 1980s and early 1990s was a period of abnormally low rainfall across many parts of the UK but particularly in south east England. This area is underlain by a number of stratigraphic units that consist mainly of clay, in particular the London Clay that underlies large parts of London and its hinterland. Clays tend to swell (increase in volume) during wet weather and shrink (reduce in volume) during dry periods. As a result of the prolonged period of dry weather the clays in southeastern England shrank more than usual. The shrinkage was exacerbated by the increased moisture requirement of trees and shrubs during the dry weather. The excess shrinkage of the ground removed support to the foundations of lightweight structures, particularly houses, causing damage to both foundations and super-structure. In the period 1989 to 1991, insurance companies lost around £1.5 billion in paying out claims.

Swelling and shrinkage of clay soils are not the only hazards that cause damage to property and financial loss. Dissolution of gypsum in the Ripon area has caused losses of several million pounds, while the Holbeck Hall landslide on the coast just south of Scarborough destroyed a hotel worth about £2M (Fig. 5). Landsliding at Nefyn, on the north coast of North Wales killed one person, injured another and destroyed two houses on 2nd January 2001. Collapse of abandoned mines has damaged houses in Reading, Newcastle and Edinburgh in the last few months, while long-abandoned mine shafts are regularly discovered, adding to the cost of development by the need to safely cap them.

These losses led insurance companies to demand an information system that could help them reduce losses by enabling them to set premiums at an appropriate level for the geological hazards found in each part of the country. The principle by which insurance largely operates is that the many pay for the misfortunes of the few. The system is based on the idea of social justice. However, the principles of natural justice suggest that those who are at higher risk should pay more than those at lower risk. Consequently, the premium paid by an individual is based on the exposure to risk of a group of individuals. The problem is to group together individuals so that the premiums paid reflect that level of risk, requiring a system that identifies the degree of susceptibility of geological hazards for defined geographical areas. This was done by using geological data, knowledge and experience to identify the local ground conditions within each postcode sector, Each geohazard could then be analysed separately, and the results of the analysis combined to produce the final ratings, taking into account possible interactions between geohazards.

There is a certain irony that, just when many national geological surveys are completing the stratigraphic mapping of their territories, when there

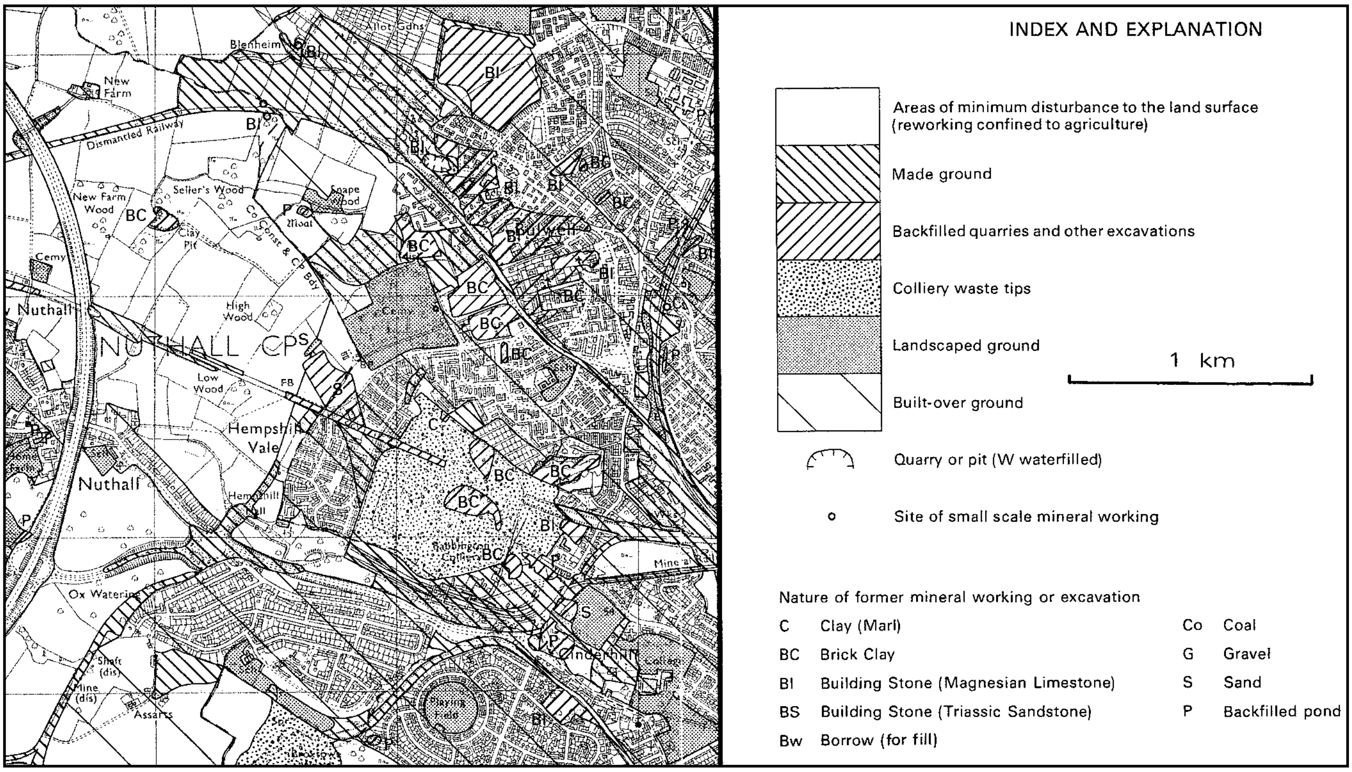

Figure 4. Extract from map 4A, *Distribution of made and disturbed ground*, in the BGS report on the applied geology of the Nottingham area (Charsley *et al*, 1990). This shows the area between Bulwell and the motorway on the west side of Nottingham, with the backfilled quarries in the Permian brick clays and Bulwell Stone and the waste heap from the old Cinderhill colliery.

is a greater awareness than ever of the requirement to meet diverse user needs and when the information technology revolution will enable the former to become easily available to the latter, the relevance of the geological survey as an active and dynamic service organisation is being questioned. It is almost as if the realisation that the paper-based geological map, as we knew it, is an anachronism which has made decision-makers believe that, maybe, the geological survey, too, is outdated. Nothing could be further from the truth.

The realisation that the paper map is the medium and not the message has liberated geological surveys from the so-called 'postage stamp collection' phase of their activity. Instead, a new phase has begun, in which the end is not the map itself but the collection and interpretation of data using the latest methods, models and theories. In other words, we are returning to the original intention of geological mapping but without the limitations placed upon it by paper sizes and printing technology. Scale is no longer a constraint; detail does not need to be at the same level across the whole country; the types of data collected can be. more easily related to the needs of the geological and non-geological user. The geological map is on the brink of a momentous digital revolution similar to the revolution that initiated geological mapping over 200 years ago. William Smith and his contemporaries must be spinning in their graves, not in anger over what has happened to the geological map but in frustration that they can't be a part of it!

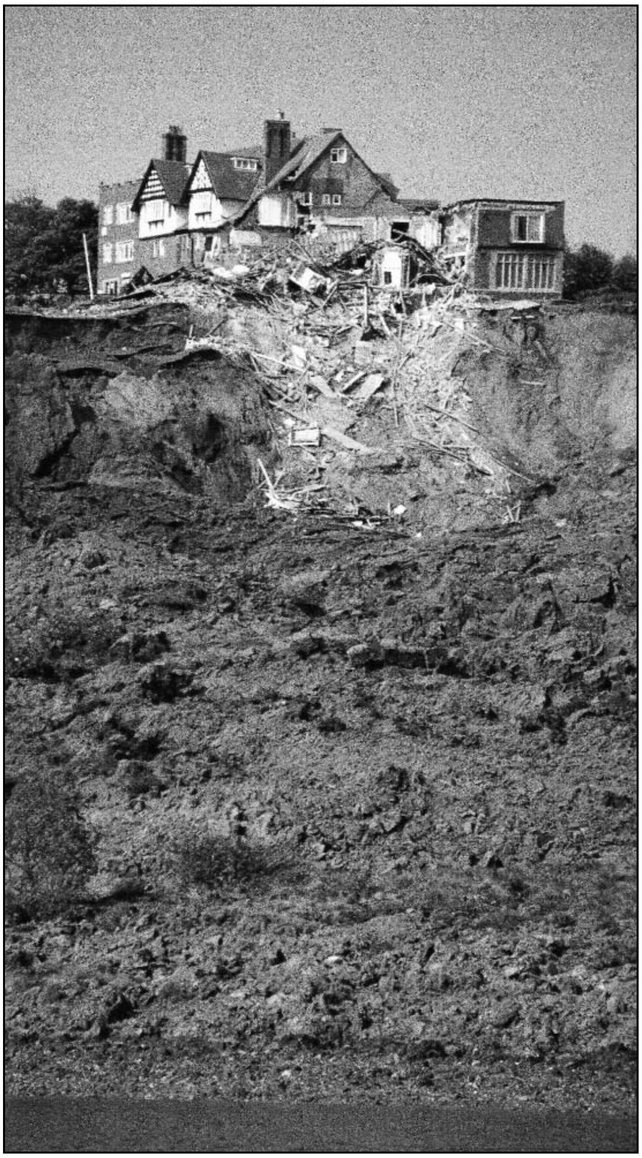

Figure 5. Wreckage of the Holbeck Hall Hotel is strewn down the headscar of the landslide that destroyed it at Scarborough in 1993.

Biographical Note

Professor Culshaw's early geological career was inspired by Fred Shotton, while a student at Birmingham. Postgraduate training followed at Leeds, and he then joined the British Geological Survey, progressing to his current position as Manager of the Urban Geoscience and Geological Hazards Programme. He has published over 70 papers and articles, co-authored over 100 technical reports and edited eight conference proceedings, as well as organising meetings and conferences. Although Nottingham doesn't have a university geology department, the East Midlands does have on its doorstep the country's principal custodian of geological knowledge - the BGS. Martin Culshaw is now Visiting Professor in Engineering Geology at the Nottingham Trent University.

Professor David Butcher - The protection of drinking water supplies in Britain

In recent years, considerable concern has been expressed that the existing infrastructure of water supply in Britain may be insufficient to maintain an adequate response to demand. This concern has been primarily related to issues of variation in supply associated with climate change scenarios, but latterly an increasing awareness of two other issues has emerged - the loss of reservoir capacity caused by sedimentation and the disruption of river extraction caused by pollution incidents.

Until recently reservoir sedimentation has not been perceived as a major problem in Britain, and there have been only a limited number of studies into the subject area. However, the cost of replacing lost capacity and the need for greater storage has caused both the government and the water companies to consider rates of capacity loss and the costs of sediment removal. British reservoirs tend to be rather old, on a global scale, and have high capacities relative to their catchment areas; they are therefore very efficient at trapping sediment. Key investigations now being pursued include measurement of the rates of sedimentation, and research into how the sediment may be removed. This is requiring a detailed survey of reservoir floor profiles and sampling of the sediments.

Figure 6. Sediment-rich water released on opening the bottom scour valve at Blakeley Reservoir, Yorkshire

There is also an issue concerning what might happen should a dam fail. The consequent increase in water velocity could cause significant additional erosion, and the dispersion of mud slurry could well cause major difficulties downstream.

River waters already account for over 55% of the potable abstraction in Britain, and are increasingly being utilised to address the escalating demand for water supplies. This brings with it a need for increased awareness about the sources of pollution that may threaten these resources. The duty of the water supply companies for the provision of ‘wholesome’ water to the consumer's tap is offset with the necessity to maintain the traditional use of river channels for irrigation, waste disposal and recreation.

The increasing pressure on the fluvial environment has lead to a steady increase in the number and severity of pollution incidents. Current research focuses on the travel and dispersion of pollution in rivers. Notable is the significance of enhanced surface run-off in urban areas and the increased sediment load of rivers in regions hosting intensive farming practices.

Drinking water is a crucial issue of life or death significance to many people. The issues of its supply are of great importance in Britain, but are of vital importance in countries where water resources are scarce. To address them requires a multi-disciplinary approach, which is being consolidated through the Geohazards Group, addressing the problems caused by reservoir sedimentation, the cost of replacing lost capacity and the need for greater storage of water.

Figure 7. Channel cut through sediments in Wessenden Old Reservoir, Yorkshire, when it was drained for repair works.

Biographical Note

Professor Butcher began his career in Higher Education studying for a BA in Geography and a PGCE at Hull University. David clinched his first position as senior tutor at the Field Studies Council, before moving to Slapton Ley Field Studies Centre as Deputy Director of Studies. He subsequently lectured at Huddersfield Polytechnic, where he also gained his PhD, studying soil water movement, before spending a period at the Peak National Park. David's next career step brought him back to Huddersfield as an academic, and then to the University of Central Lancashire. David Butcher is now Professor in Engineering Hydrology at the Nottingham Trent University, and Head of the newly formed Department of Land-Based Studies, located at its Brackenhurst College Campus in Southwell.

Acknowledgements

These synopses of the inaugural lectures were all prepared from the original abstracts and notes written by Professors Mike Rosenbaum, Ian Smalley, Martin Culshaw and David Butcher. The Nottingham Trent University has a strong Geohazards Research Group, whose members freely discuss and exchange their views in their quest to develop a better understanding of ground and its impact on the built environment

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Prof. M. S. Rosenbaum,
School of Property and Construction,
Nottingham Trent University,
Nottingham NG1 4BU

Geology and building stones in the East Midlands

Graham Lott

Abstract. The East Midlands has a diverse heritage of stone buildings reflecting the varied character of the regions geological strata. The principal stones used in the buildings of the area are described and identified and placed in their modern stratigraphic context. This very diversity, however, while providing a colourful backdrop to the villages and towns of the area for all to enjoy, presents an increasing problem to those concerned with conserving these structures, as many of the stones are now no longer quarried.

With the increasingly rapid expansion and development of our cities, towns and villages, by the addition of rather bland, mass-produced brick built housing developments, metal clad factories and glass-fronted office blocks, the end of a millennium is perhaps a particularly suitable time to reflect upon the diverse and colourful use of local building materials in the past.

The East Midlands has a distinctive character which is well expressed in the wealth and variety of vernacular buildings it has produced over the last millennium, many examples of which still survive. It is evident that locally quarried building stone and locally produced bricks have played an important part in moulding this character. The picturesque and attractive gritstone or limestone cottages of the Derbyshire Peak District are familiar to most people through endless images on calendars and in local publications. However, the other counties of the region have equally attractive and perhaps more diverse, though less well publicised, stone built heritages.

This contribution will focus on identifying the many varieties of local building stone used in the area, their distribution and, where possible, the location of their original quarry sources (Fig. 1). By placing these stones in their modern geological context, following the many changes in stratigraphic nomenclature which have taken place over the last few decades, it is possible to avoid perpetuating some of the misconceptions regarding stone sources found in earlier literature. In a study of any aspect of the buildings of the area the books in the series *The Buildings of England*, particularly the later revised editions, are essential reading (Pevsner, 1979, 1992, 1993; Pevsner and Harris, 1995).

Many of the stones described in the following account would probably not pass the stringent engineering tests required for the very different demands of today's building stone market. Many are stones used in limited areas, perhaps only for a few local houses. However, they have all survived several centuries of exposure to the elements and, without the problems of decay caused by modern airborne pollutants, would in many cases probably survive another thousand years.

Publications concerned with the building stones of an area are often focused on their use in the archaeology or conservation of historic structures. However, the building stone industry has never been concerned with providing stone solely for conservation purposes. Today, stone quarrying in the East Midlands area for new building work, such as the Law Courts in Nottingham (Birchover Stone), town centre developments at Bakewell (Stanton Moor Stone) and the new visitor centre at Southwell Minster (White Mansfield Stone), is still an important part of the local economy.

A study of building stones necessarily involves not only an understanding of the stone and its geology, but also some knowledge of a building's history, its building methods and local historical context. It is quite common to find that stone buildings have been restored or extended at different periods in their history, sometimes using stone from the original quarries but in more recent times using stone imported from elsewhere.

In broad terms the stone buildings of the East Midlands can be divided into three types. The first includes high-status buildings in which the use of particular building materials was generally not constrained by proximity to the quarry source or transportation costs; this category principally includes larger buildings constructed prior to the middle of the 18th century, such as castles, stately houses, abbeys, cathedrals and larger churches. The second comprises smaller vernacular houses, parish churches and smaller industrial buildings such as windmills and mine buildings, where local materials would almost certainly be preferred on cost grounds. The third includes larger industrial buildings dating from the end of the 18th century and closely related to the development of canal and, later, the rail networks which markedly increased both the variety and availability of stone for building by dramatically reducing transportation costs. Included in this last category are both the factory buildings in the new industrial centres and the rapidly expanded housing developments for the growing workforces that supported the new industries.

The East Midlands area, which is taken here to arbitrarily include the counties of Derbyshire,

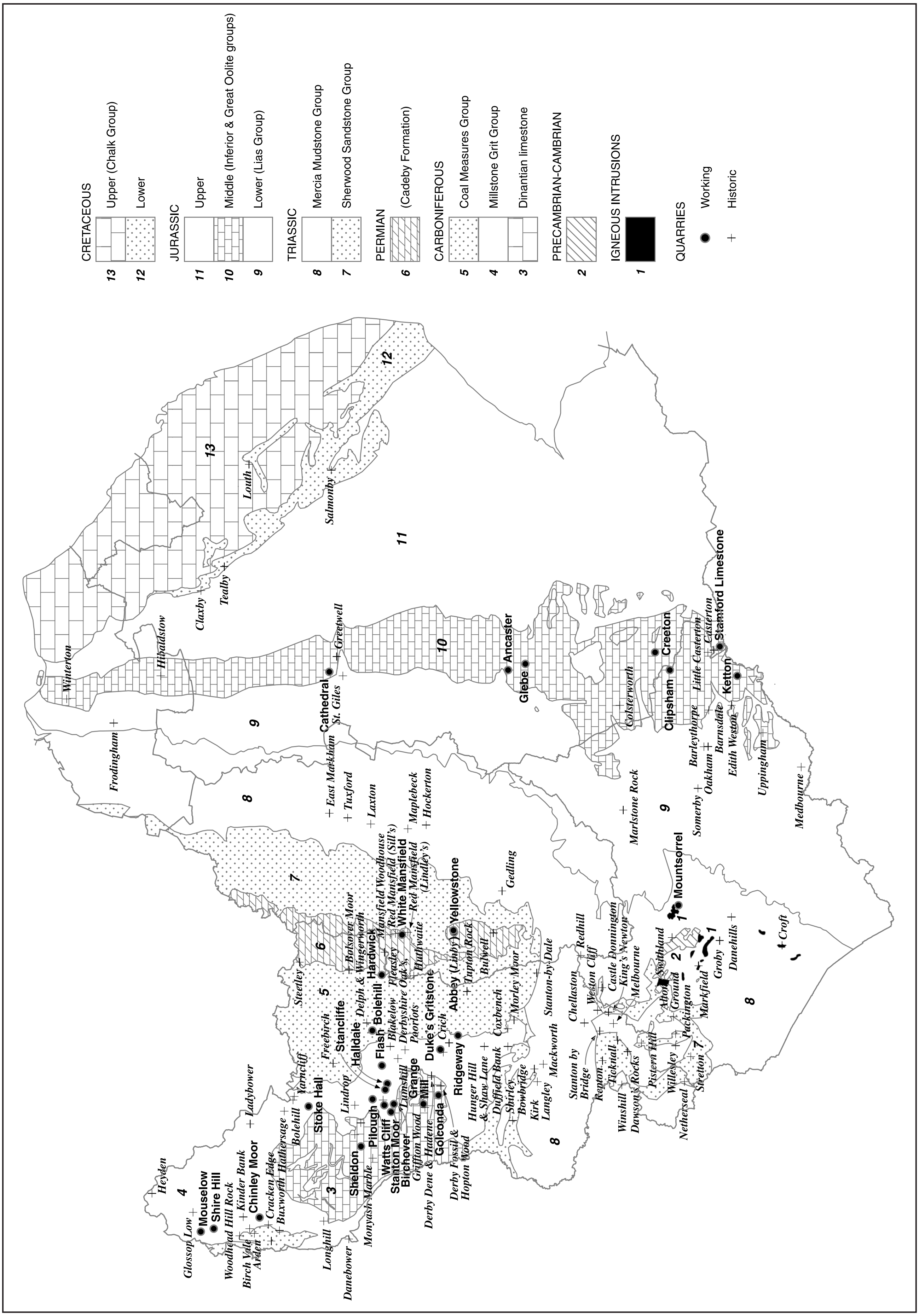


Figure 1. Geological map of the East Midlands, with locations of the main building stone quarries.

Leicestershire (including Rutland), Lincolnshire (including South Humberside) and Nottinghamshire, has long been a significant producer and exploiter of its indigenous stone resources for building purposes. Many of its working quarries are still important building stone sources and exporters in a national context.

Geologically, the East Midlands has a core of mildly metamorphosed Precambrian to Cambrian basement rocks, forming the high ground of Charnwood Forest, surrounded and overlain by a series of more or less conformably dipping sedimentary rock units, ranging from Early Carboniferous to Late Cretaceous in age. In Leicestershire and Derbyshire various igneous rocks have been intruded into this sedimentary cover during the early Palaeozoic and are now also exposed at the surface. The widely contrasting stones used in the buildings across the East Midlands are a product of this geologically varied rock succession.

Precambrian (Charnian) rocks

The rocks of the Charnwood area form a small inlier of folded late Precambrian metamorphosed volcaniclastic rocks – the Charnian Supergroup (Carney, 1999; Carney *et al.*, 2000) cut by Precambrian intrusions of granophyric diorite (Markfeldite – South Charnwood Diorite)) and diorite (North Charnwood Diorite). The geological complexities of the succession are still the subject of debate, but for present purposes the interval comprises the lithologically heterogeneous Blackbrook and Maplewell groups, each of which is divided into a number of formations and members (Table 1).

The Blackbrook Group, forming the core of the anticline, is predominantly a metavolcaniclastic sequence with breccias, sandstones and finer grained lithologies. The overlying Maplewell Group is dominated by interbedded fine and coarse-grained, tuffaceous volcaniclastic rocks and breccias. Particularly distinctive units within this latter group are the Whitwick and Bardon Hill intrusive volcanic complexes, which include the coarsely crystalline, green and speckled white (quartz-feldspar crystals) Peldar Dacite.

		Group	Formation	Member	Principal Volcaniclastic Lithotypes	Building Stone Quarries
Cambrian		Brand	Swithland		Slate	*Swithland, Brand Groby, Woodhouse Eaves*
			Brand Hills	Hanging Rocks Conglomerate	Pebbly Conglomerate	
Precambrian	Charnian Supergroup	Maplewell	South Charnwood Diorite Intrusions		Diorite	*Groby, Markfield*
			Bradgate		Sandstones Breccia	
			Beacon Hill		Sandstones	
				Charnwood Lodge	Volcanic tuffs	
				Whitwick Complex	Breccia, Porphyritic Dacite	*Whitwick Bardon Hill*
		Blackbrook	Blackbrook Reservoir		Sandstone Breccia	
			Ives Head	South Quarry Breccia Lubcloud Greywackes Morley Lane Tuffs	Breccia Sandstone with convolute bedding, lamination, grading	*Ringing Hill* *Morley*
			Morley Lane Volcanics		*Not seen at outcrop*	

Table 1. Precambrian stratigraphy and building stone quarries of the East Midlands.

Precambrian building stones

This relatively small outcrop has one of the most diverse rock successions in the East Midlands area. Many of the lithologies present are properly identifiable only in thin section and their individual recognition in local buildings generally requires a thorough knowledge of the rock succession. However, it is possible to attribute most of the building stone lithologies encountered in and around the area to a generic 'Charnian' suite of rock types. The hard nature of the Charnian metasediments has meant they have principally been used as local building and walling stone and are rarely found outside the immediate area of their outcrop. No single lithological unit from this interval has been systematically worked for building stone and a mixture of litho-types from the succession can commonly be seen in local buildings.

The Charnian rocks used as building stone exhibit a wide variety of colours, lithologies and textures from off-white to dark grey-green and purple with micaceous, fine-grained and coarse-grained textures. They have been used in building construction since Roman times and can be seen in the Jewry Wall in Leicester and in the remnants of Ulverscroft and Grace Dieu priories built in the 12th century (12C). More recently Mount St Bernard Abbey (19C) and Blackbrook Reservoir (20C) were constructed using a variety of Charnian lithologies. Characteristically these hard intractable rocks are seen in buildings as uncoursed, polygonal, random rubble stone and are rarely shaped or sawn (ashlar) block. Examples of the lithological variations that occur and building styles used are displayed in churches in Leicester (St Mark and St. Nicholas churches), Loughborough, Long Whatton and Belton, and in village housing in Osgathorpe (Plate 1A).

The Cambrian Rocks

Overlying the Charnian succession are the finer grained lithologies of the Brand Group. The overlying Brand Group was formerly included in the Charnian Supergroup but has recently been reassigned to the Lower Cambrian (Bland, 1994). The succession includes the greywacke sandstones and siltstones of the Swithland Formation which commonly show a metamorphically-induced, coarse slatey cleavage. They can be split along these irregular cleavage planes into slabs c.100 mm thick.

Cambrian building stones

This succession is perhaps best known as the source of the Swithland Slates, the focus from the early 18th to late 19th centuries of an important local stone industry. The slates are typically purple, dark grey or green-grey in colour and were widely used for roofing but also for wall stone. They are particularly well displayed in the roofs and walls of houses in Woodhouse Eaves (Plate 1B), but scattered examples of their use as roofing slates survive in many of the villages surrounding the original quarries.

The main quarries were at Brand, Groby, Swithland Wood and Woodhouse Eaves, but are long abandoned and flooded. In its heyday the Swithland Quarry was worked to a depth of 55 m and the stone blocks had to be raised to ground level by crane for splitting, cutting or polishing. Evidence for the long exploitation of Swithland Slates is found in their usage as roofing material on Roman buildings in Leicester (*Ratae*) and at Margidunum near East Bridgford, Nottingham. The recorded production figures from the industrial minerals survey carried out by Hunt (1860) provide some indication of the scale of the industry. At that time (figures for 1858) annual production from the slate quarries at Groby and Swithland Wood was 1000 and 2000 tons respectively. By comparison annual production was 10,000 tons at the Burlington slate quarries at Kirby in Cumbria, and about 90,000 tons at the Dinorwic quarries in North Wales. It is easy, therefore to see why, after the development of the railways, the Swithland quarries quickly went into decline. The last Swithland slate quarry had closed by about 1888 (Crocker, 1981).

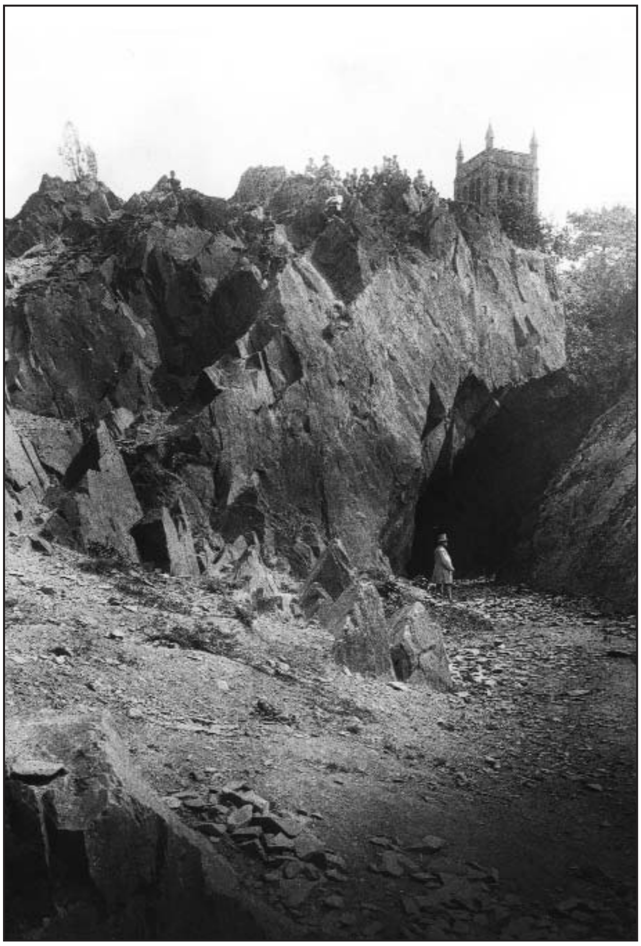


Figure 2. Swithland Slate quarry at Woodhouse Eaves, Leicestershire in 1894 (British Association photo #938).

The other important use for Swithland Slate was for intricately lettered and carved headstones or memorial plaques, many of which survive in the churches and graveyards of Leicestershire, Rutland, south Nottinghamshire and west Lincolnshire (Barley, 1948; Burgess, 1954; Herbert, 1945). The Swithland slates headstones can be distinguished from the later Welsh imports, some of which can be similar in colour, by the characteristic natural undulations on the unpolished back surface of the slabs.

Intrusive igneous rocks

The Precambrian-Cambrian succession of Charnwood and adjacent areas was extensively affected by igneous activity both during the Precambrian and Lower Palaeozoic. Most of the resulting exposed intrusive igneous bodies are currently being exploited for construction materials. These coarse-grained rocks, often described in early literature as syenites, are in fact a much more varied rock suite. Compositionally the Lower Palaeozoic intrusions are a complex mixture of diorite (dark coloured, containing no potassic-feldspar and little or no quartz), granodiorite (containing quartz, pink potassic-feldspars and grey plagioclase) and tonalites (dark coloured, with no potassic-feldspar, and low quartz). Their outcrops are concentrated in three areas that are compositionally distinct (Worssam and Old, 1988).

In south Leicestershire, the Lower Palaeozoic diorites crop out around Enderby (dark purple grey with pink feldspar), Yennards and Barrow Hill (dark grey, porphyritic, microdiorites with feldspar phenocrysts 2 mm long), Huncote and Croft (coarse pink and dark greenish brown) and Stoney Stanton (dark medium to coarse quartz diorite). In south Charnwood Pre-Cambrian diorites have been quarried at Groby (coarse-grained, purple and green mottled) and Markfield (granophyric textures; coarse-grained, pink and greenish grey feldspars, with some silica and darker green ferromagnesian minerals). The feldspar crystals are characteristically tabular and equant. In north Charnwood the Precambrian diorites are coarse-grained but darker in colour (dark grey) than the southern Markfieldite varieties. Probably the most readily recognised of these intrusive rocks is the Ordovician Mountsorrel granodiorite. This is pink to grey in colour, coarsely crystalline and silica-rich with both pink potash and grey plagioclase feldspars.

Igneous building stones

All the igneous rocks can be identified in local buildings in the area. Few, however, achieved any real individual success as building stones and they usually occur within a mixture of lithologies in walls or buildings. The exception is perhaps the red Lower Palaeozoic granodiorite of the Mountsorrel quarries. Most famous, perhaps, for the production of kerbstones and setts which were exported to cities and towns across the country from the early 19th century, it was used long before then as a local building stone. A very hard and intractable stone, it was commonly used as large irregular rubble stone blocks in the walls and houses of older buildings in villages around the quarries. In the 19th century numerous local churches and houses were constructed or 'restored' using large blocks of dark red Mountsorrel granodiorite. Many examples can be seen in churches and houses in Leicester (St. Paul) and at Mountsorrel, Quorndon, Barrow-on-Soar and Hoton. The distinctive green coloration of the coarse-grained diorite of the Markfield quarries is also readily identified in the walls of buildings in and around Groby and other examples of its use include 19th century wall buttresses at Diseworth church. Rothley church includes diorite from quarries at Stoney Stanton.

The Carboniferous rocks

The oldest unmetamorphosed sedimentary rocks that crop out in the East Midlands are of Upper Palaeozoic age and are restricted to the western part of the area. They comprise the early Carboniferous (Dinantian) limestone-dominated succession of western Derbyshire, the famed White Peak area, together with the isolated limestone inliers of north-west Leicestershire. Conformably overlying this limestone succession are the important sandstone resources of the Namurian (Millstone Grit Group) and Westphalian (Coal Measures) successions, largely concentrated in the equally famous Dark Peak area and the south Derbyshire-Leicestershire coalfield. The stratigraphy of the Carboniferous sequence is summarised in Tables 2 and 3.

Stone buildings occur extensively throughout the Derbyshire Peak District. The stones used in the higher status or country houses of the 'gentry' have been exhaustively documented by Craven and Stanley (1991). In their research they also identified a number of the larger building stone quarries in the area. However, many more local quarries supplied stone for village houses, farms and moorland barns and later for the housing demands of the new industrial towns. The harsh climate of the moorland areas of the Peak District also demanded a particularly good roof covering and the local fissile sandstones were extensively worked for thick roofing slates. These 'grey slates' were generally used within the county and only rarely appear farther afield.

		Stage	Formation		Building Stone Quarries
			BREEDON AREA	*WHITE PEAK AREA*	
Dinantian	Visean	Brigantian	Ticknall Limestone	Monsal Dale Limestones	*Grace Dieu*
		Asbian	Cloud Hill Dolostone	Bee Low Limestones	*Griffeton Wood* *Hopton Wood* *Sheldon* *Grange Mill*
		Holkerian	*absent*	Woo Dale Limestones	
		Arundian			*Ashford in the Water* *Hognaston*
	Tournaisian	Chadian	Milldale Limestones		*Breedon Hill*
		Courceyan	*absent*		

Table 2. Lower Carboniferous stratigraphy and building stone quarries of the East Midlands.

The earliest survey of the building stone quarrying activities of Derbyshire was carried out by Farey (published 1811). He listed 180 freestone quarries in operation at the time. Of these, two were working Carboniferous limestones and 143 Carboniferous sandstones. The remainder included 24 quarries working sandstones of Triassic age, 11 the Permian Magnesian Limestone and two in Pleistocene tufa deposits. Currently, there are 22 Carboniferous sandstone quarries and four limestone quarries producing building stone in Derbyshire.

Lower Carboniferous building limestones

The geology of the limestones of the White Peak is now known in some detail and mapping has defined clear lithological changes across the outcrop. These variations have been related to changes in depositional environments, most specifically to marked difference in water depths across the sedimentary basin (e.g. Harrison and Adlam, 1985; Miller *et al.*, 1987). The pale grey, fossiliferous limestones, often termed *Mountain Limestone* in older literature and typical of the White Peak outcrop, were principally formed in high energy shallow water, reef and shelf environments. Good examples of their use as building stone can be seen in Matlock and in village housing at Tissington and Carsington (Plate 1C). Adjacent to this main shelf limestone development, deeper water limestones were deposited which are finer grained, laminated and characterised by layers of siliceous chert. Limestone blocks containing these dark brown to black, layered chert bands are a common feature in the wall fabrics of houses in Hognaston village (Plate 1D), lying to the south of the main shelf limestone outcrop area. They can also be seen in buildings in Ashford-in-the Water, which lies to the east of the main shelf limestone area.

Despite the relatively few building limestone quarries identified by Farey (1811), it is evident from the older housing stock of the outcrop area that the local limestone is the primary building material. The building styles and date-stones present suggest that quarrying has been important in the White Peak area since at least the 17th century. In village housing the grey, coursed limestone wall fabrics often contrast with brown Carboniferous sandstone ashlar blocks which were used for window and door surrounds, as at Bonsall and Parwich (Wright, 1985). Haddon Hall provides another fine example of this early polychromatic building technique. Numerous disused quarries can be identified throughout the area, but many probably yielded products other than building stone, namely agricultural and building lime. Each village, or indeed any sizeable house or farm in the area, is likely to have had its own local building limestone quarry source.

The Carboniferous limestones of the Derbyshire area have also long been famous for their decorative stone production. Commonly termed ‘marbles’ by the trade, due to their attractive colours and varied internal fabrics, and because their hardness allowed them to take a high polish, they were quarried in a number of localities. These ‘native marbles’ included Ashford Black, Bird’s Eye (black with white crinoid fragments), Coralline (grey mottled), Derby Fossil (grey, crinoidal), Rosewood (pink layered), and Duke’s Red (deep red with shades of yellow) (Farey, 1815; Ford, 1958). None of these stones is now produced, but their former local importance is evident from their extensive use as decorative adornments in many of the Great Houses of the Derbyshire area such as Chatsworth, Hardwick, Haddon and Bolsover Castle. Derbyshire marbles were recorded in the early 18th century as part of the trade goods carried along the Don Navigation to the Humber Estuary ports (Hey, 1980).

The more coarsely fossiliferous crinoidal and coraliferous limestone beds, representing original shallow shelf, reefal developments, have commonly been quarried for decorative use. Formerly the Derby Dene and currently the Once-a-Week quarries near Wirksworth produce pale grey, polished crinoidal limestone slabs. Decorative crinoidal limestones slabs, probably sourced from the Derbyshire quarries, can be seen in churches throughout the area, e.g. St. Peter’s and St Margaret’s in Nottingham. Polished limestones are still produced from the Bee Low Limestone Formation at the Hopton Wood and Griffeton Wood quarries. The original Hopton Wood Stone, which is a pale buff coloured limestone, spotted by white crinoid fragments, has been used in many major buildings including the Bank of England and the city halls of Manchester and Sheffield. On a more sombre note the Hopton Wood quarry provided the headstones marking the overseas graves of tens of thousands of British and Commonwealth troops who fell in the First and Second World Wars, and was also frequently specified for war memorials throughout Britain.

South of this main limestone outcrop, several small, fault-bounded Dinantian limestone inliers occur in north Leicestershire, stretching from Ticknall southwards through Breedon to Grace Dieu. Though extensively quarried in the past for lime at Ticknall, and today for aggregate at Breedon, they were also used locally as building stone sources. The limestones are variably dolomitised and show a range of colours from reddish brown to grey. Examples of their local use can be seen in the fabrics of the churches and houses at Osgathorpe, Breedon-on-the-Hill and in surrounding hamlets. The hard limestone is commonly used in randomly coursed rubble style giving some buildings a distinctive polygonal wall fabric. Adjacent to the former abbey at Grace Dieu is the small quarry from which stone for parts of the Abbey fabric was obtained. In the surviving wall remnants, the local Milldale Limestone, notable for the large brachiopod fossils present, is mixed with a variety of Charnian lithologies.

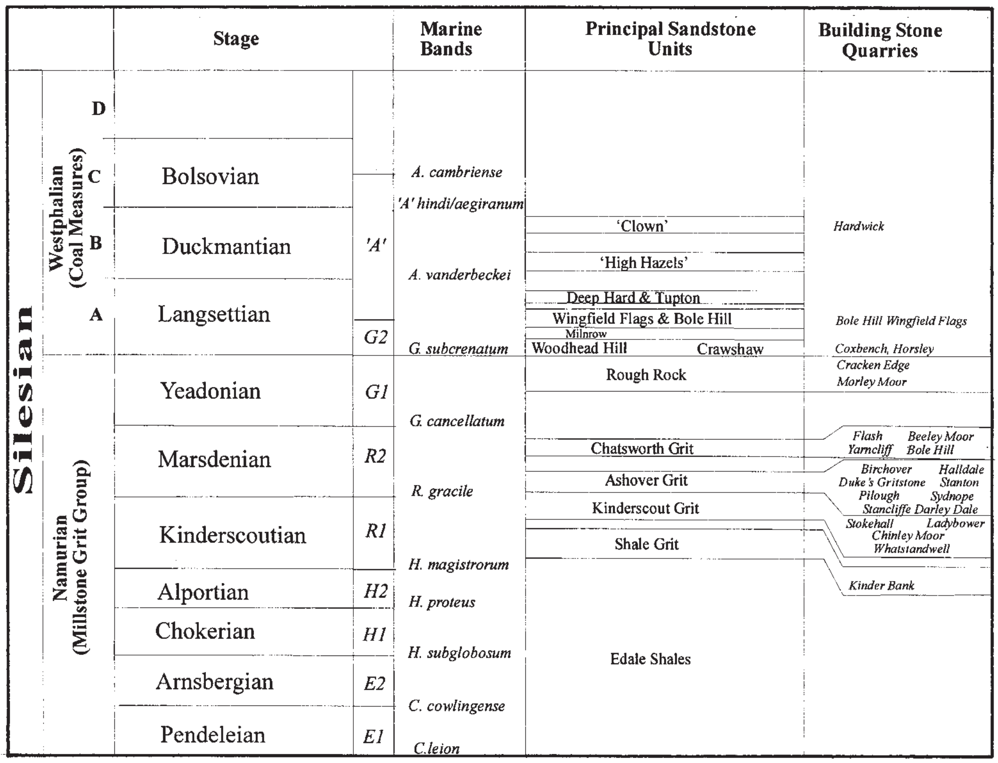
Namurian building sandstones

The sandstone beds of the Millstone Grit Group have been widely quarried for building stone in Derbyshire and to a lesser extent in north-west Leicestershire (Table 3). The fluvio-deltaic succession is characterised by thick, massive-bedded, channel sandstones, thinly bedded sandstones and mudstones. The hardness and resistance to weathering of the sandstones are clearly evident in the steep gritstone edges that dominate the local scenery.

Petrographically the sandstones range from quartz arenites (quartz-rich) to arkoses (feldspar-rich), but beyond the fact the stones quarried for building purposes are all sandstones, there is no ‘typical’ Millstone Grit lithology. Different quarries in the county have worked beds of varied colour, lithology and thickness. The thinly bedded varieties were extensively exploited for flag or roofing stone in the past while the more massive beds were favoured for high quality sawn stone lintels, mullions etc. and ashlar block. Today few quarries work the fissile beds for roofing ‘slate’ and new sources are being sought out. The block stone industry, however, is still thriving and supplies builders throughout Britain, where the Carboniferous sandstones are often known collectively as York Stone.

The sandstones used in buildings show a wide variety of colours, commonly from grey to brown to buff, but the variable iron content produces yellow or reddened varieties in some areas. Lithologically they vary from fine grained, well sorted sandstones to coarser, poorly sorted, quartz pebble-rich varieties. Some sandstone blocks show pronounced cross-bedding or horizontal lamination, while others appear to be more homogeneous in character. It is these changes in the sandstones that provide subtle differences in the character of local buildings across the outcrop.

Table 3. Stratigraphy of the Upper Carboniferous, and its quarries sites for building stone within the East Midlands.



			Stage		Marine Bands	Principal Sandstone Units	Building Stone Quarries
Silesian	Westphalian (Coal Measures)	D					
		C	Bolsovian	'A'	A. cambriense 'A' hindi/aegiranum		
		B	Duckmantian		A. vanderbeckei	'Clown' 'High Hazels'	Hardwick
		A	Langsettian	G2	G. subcrenatum	Deep Hard & Tupton Wingfield Flags & Bole Hill Milnrow Woodhead Hill Crawshaw	Bole Hill Wingfield Flags Coxbench, Horsley
	Namurian (Millstone Grit Group)		Yeadonian	G1	G. cancellatum	Rough Rock	Cracken Edge Morley Moor
			Marsdenian	R2	R. gracile	Chatsworth Grit Ashover Grit	Flash Beeley Moor Yarncliff Bole Hill Birchover Halldale Duke's Gritstone Stanton Pilough Sydnope Stancliffe Darley Dale
			Kinderscoutian	R1	H. magistrorum	Kinderscout Grit Shale Grit	Stokehall Ladybower Chinley Moor Whatstandwell Kinder Bank
			Alportian	H2	H. proteus	Edale Shales	
			Chokerian	H1	H. subglobosum		
			Arnsbergian	E2	C. cowlingense		
			Pendeleian	E1	C.leion		

In the Derbyshire Peak District, the exploitation of the Namurian sandstones has a long history and the area is pockmarked by old sandstone quarry workings. All the major sandstone beds have been quarried locally, the majority for local building use, but a number have attained national importance for the quality of their stone (Farey, 1815; Stevenson et al., 1971; Smith et al., 1967). Many of the smaller abandoned quarries, particularly in the north east of the county and across the border into Yorkshire, probably relate to the production of the famed 'Peak Millstones', dating back to medieval times (see below).

In the High Peak area of north Derbyshire, sandstones have been extensively worked in the past from the Shale Grit at Kinder Bank, the Kinderscout Grit at Chinley Moor, Lady Bower and Stokehall, the Heyden Rock at Thornseat, the Ashover Grit at Combs, Ridge Hall and Longhill), the Chatsworth Grit at Birch Vale, Buxworth, and the Rough Rock at Cracken Edge.

The most important areas of sandstone quarrying in Derbyshire, however, lie along the Derwent and Amber valleys and the hillsides between. Here, the Namurian sandstones are exposed in the valley sides from Hathersage to Belper. Quarries have long worked the Kinderscout Grit at Hayfield and Whatstandwell, the Ashover Grit at Duffield Bank, Darley Dale, Birchover, Pilhough, Duke's and Stanton Moor) and the Chatsworth Grit at Yarncliff, Grindleford, Beeley Moor, Lumshill and Millstone Edge.

The Stancliffe Darley Dale Stone (Ashover Grit) was famed for its durability and quality and has been widely used in surrounding towns and cities (e.g. Derby Cathedral; St. George's Hall, Liverpool; Royal Exchange, Manchester; the Town Hall, Birmingham). The Ashover Grit used in the buildings in the village of Kirk Ireton is stained pinkish red from the percolation of groundwaters through the former Triassic red-bed cover (Frost and Smart, 1979). The Shale Grit sandstone at Bolehill Quarry was used for the Kinder reservoir, and Stoke Hall Stone (Ashover Grit) from the Grindleford quarries for the Howden and Derwent reservoirs and Sheffield Town Hall. Large sandstone quarries once worked the Rough Rock at Morley Moor.

One of the characteristic features of the Derbyshire Peak District are the large stone roofing slates that once covered almost every stone built house. Today these original stone slate roofs are much harder to find as they have been replaced by Welsh slates and even clay and concrete tiles. Stone slates were once quarried extensively throughout the county and Farey (1815) lists about 46 slate quarries in operation. Most were small-scale producers but some later become quite large operations e.g. Glossop Low and Goytsclough. The 'slates' were obtained from both Namurian and Westphalian sandstones, and quarries were concentrated from Glossop southwards to Whaley Bridge, along the Derwent valley around Hathersage and between Matlock and Chesterfield. The main stone slate quarries have been documented by Hughes (1996).

Farther to the south, separated from this main Carboniferous outcrop by Triassic strata, are the Millstone Grit and Coal Measure rocks of the Derbyshire-Leicestershire Coalfield. There, the

Namurian sandstones, though no longer quarried, have been used for building stone for centuries. The imposing Norman church at Melbourne is a fine example of its local use. The Chatsworth Grit was worked in the past around Melbourne and Stanton-by-Bridge and the Rough Rock around Dawson's Rocks (Fox-Strangways, 1905).

Sandstones interpreted on their lithological character as being from the Millstone Grit Group, appear sporadically in 10th and 11th century church buildings in north Lincolnshire, along the southern shore of the Humber Estuary (e.g. Alkeborough, Whitton church); the long and short Saxon stonework of the tower at St. Peter's Church, Barton on Humber). Evidence from archaeological research suggests that these sandstone blocks were probably recycled from earlier Roman buildings in south Yorkshire (Stocker, 1990). The precise quarry provenance for these sandstones is still unclear but their considerable size and distribution pattern along the estuary testify to a fairly sophisticated system of local river transportation at the time.

Coal Measures building sandstones

In Derbyshire, the sandstones of the Coal Measures have been used locally for building since Roman times (e.g. the site at Ockbrook). Generally finer in grain-size than the Millstone Grit sandstones, petrographically they are very similar, consisting of both quartz arenites and sub-arkosic sandstones. Numerous small quarries once existed but no large-scale sandstone exploitation has taken place except in the Crawshaw Sandstone and Wingfield Flags (Table 3).

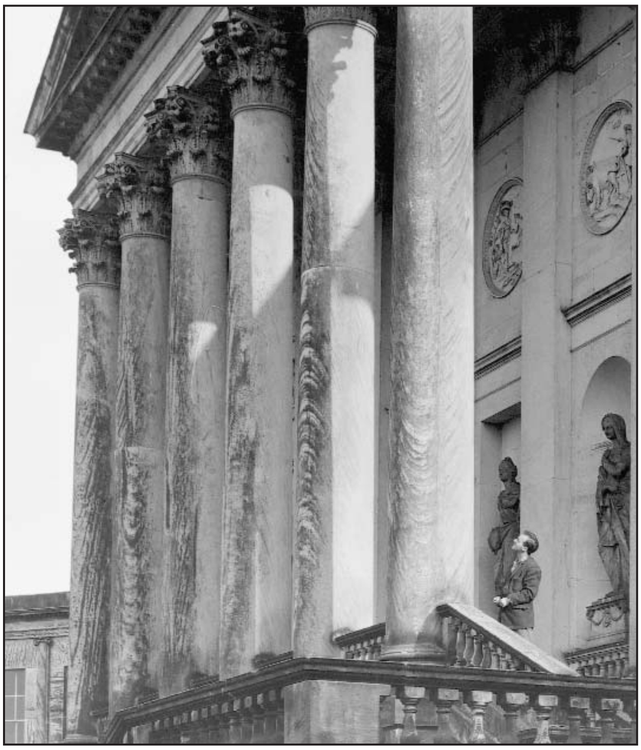


Figure 3. Kedleston Hall, Derbyshire, built 1759-63: north portico with massive columns of cross-bedded sandstone quarried from the Crawshaw Sandstone at Horseley Castle (BGS photo #L892, 1966).

In the High Peak area the Woodhead Hill Rock and the Milnrow Sandstone have been worked around Whaley Bridge. Farther to the south and east the Crawshaw Sandstone was extensively worked in the Holymoorside, Alton and Woolley areas. Large quarries formerley exploited the Wingfield Flags (locally known as the Greenmoor Rock) for building stone, paving and roofing slates at Freebirch to the west of Chesterfield. The flags continue to be worked at Bole Hill Quarry, Wingerworth. The 15th century manor house at South Wingfield was built with Wingfield Flags sandstone quarried from Crich Moor. Stone for houses in the village itself, was presumably worked from local sandstone outcrops, although grander houses are of ashlar blocks, probably from the same quarries as the manor (Plate 1F).

Some quarries, like the one operating within the estate of Hardwick Hall, were opened solely to supply stone for the hall and estate buildings. The original and 'new' halls, which sit on Permian strata, were built with Middle Coal Measures Hardwick Sandstone (Chisholm, 2001, *pers comm.*) that crops out beneath the Clown Coal seam in the low escarpment just southwest of the present hall. One of the characteristic features of this sandstone is the presence of liesegang rings in many of the blocks, a result of iron precipitation from fluids flowing through the pore space of the rocks. Current conservation requirements for the hall are, however, being met from a different sandstone below the High Hazels Coal exposed in a quarry northeast of the hall.

Farther south, the Westphalian Coal Measures are best known for their coal reserves, but they also contain prominent sandstones, which in the past have been quarried extensively for local building stone. Few of the sandstone units in this part of the coalfield area have been formally named on Geological Survey maps, making reference to specific sandstone units difficult. Sandstone quarries for building stone are known to have operated along the eastern side of the Erewash Valley around Trowell. Gibson *et al.*, (1908) suggest, however, that the general '*absence of quarries is due to the lithological composition of the sandstones*', dominated by micaceous, laminated varieties with only a few massive beds, which '*renders them unsuitable for building and other purposes*'. In older buildings in the area it is evident that the local stones were widely used for building purposes as at Beauvale Priory and Dale Abbey. Large sandstone quarries once worked the Crawshaw Sandstone at Stanton-by-Dale and Kirk Hallam (Stanley, 1990). The same sandstone from the Coxbench or Horsley quarries was also used extensively for the construction of Kedleston Hall and buildings in Derby and elsewhere (Gibson *et al.*, 1908, 1913).

Millstones and grindstones

It would be difficult to leave the subject of Upper Carboniferous sandstones, particularly those of the Millstone Grit Group, without at least a brief mention of their importance locally and nationally as sources of millstones and grindstones. Primarily known as a source of millstones for grinding flour and corn in water and wind mills from at least the 13th century (Polak, 1987), they were also used as pulping stones in the paper industry and in the paint-making industry (Radley, 1963). The sandstones were also a major source for grindstones and played an essential part in the growth and development of the tool and cutlery trade of Sheffield and the needle producing industry in Hathersage.

Important millstone quarrying areas included Stanage Edge, Hathersage Moor (Millstone Edge and Burbage), Froggatt to Baslow (all working Chatsworth Grit). From Hathersage the millstones were transported overland to the river port of Bawtry, for onward shipment to Hull and beyond (Radley, 1963; Polak, 1987). To understand something of the scale of the industry, even at a late stage in its history, it is only necessary to take a short walk over the moors between Longshaw and Hathersedge, where hundreds of partly finished millstones lie abandoned following collapse of the industry in the late 19th century.

The grindstone trade in Derbyshire (and south Yorkshire) had requirements different from that of the millstone trade (Radley, 1963). Grindstones for tool sharpening were generally finer and more even-grained and came in all shapes and sizes. Farey (1811) listed 17 Derbyshire grindstone quarries scattered across the county, using Namurian (at Beeley Moor and Ashover), Westphalian (around Bolsover, Belper, Stanton by Dale and Stanley) and Triassic (at Darley Moor) sandstones. This trade was eventually destroyed by the introduction of manufactured abrasive stones in the late 19th century.

Formation	Former Names	Building Stone Quarries
Roxby Formation	Upper Marl	
Brotherton Formation	Upper Magnesian Limestone	
Edlington Formation	Middle Marl	
Cadeby Formation	Lower Magnesian Limestone	*Bolsover* *Bulwell* *Linby* *Strelley* *Mansfield White* *Mansfield Red*
Permian Basal Breccia		

Table 4. Permian stratigraphy and building stone quarries of the East Midlands.

The Permian rocks

Rocks of this age unconformably overlie the Coal Measures. The heterogeneous succession can be subdivided into a lower unit of breccias and shales, a middle unit of orange-brown or buff-coloured dolomitic (or magnesian) limestone (the Cadeby Formation), and an upper interval in which red clays (often termed marls) and sandstones predominate (Table 4). Of these lithologies, the dolomitic limestone unit, which forms a narrow outcrop and prominent west-facing escarpment along much of the Derbyshire-Nottinghamshire border, is the main source of building stone both in the past and today.

Cadeby Formation building limestones

The Cadeby Formation, formerly known as the Lower Magnesian Limestone, is the most important source of building stone in Nottinghamshire. These limestones were once quarried extensively in the Bulwell, Cinderhill, Linby and Mansfield areas and farther north around Steetley (Metcalf, 1894). Numerous other smaller quarries along the outcrop produced local stone for building. Lithologically the limestones are very varied, ranging from coarsely crystalline dolomites and sandy (quartz-rich) dolomites in the south, to bioclastic (shell- and bryozoan-rich), oolitic and pisolitic varieties farther north. Each of these lithological varieties can, with a little care, be identified in buildings all along the outcrop.

At the southernmost limit of the outcrop around Nottingham, the Bulwell and Linby quarries dominated production. These yellow-brown to orange, coarsely crystalline limestones with thin, discontinuous, pale greenish-grey clay seams were much in demand in the past for housing, churches, schools and factories in Nottingham. The original Bulwell (Golden) Stone quarries appear in documents as far back as the 16th century. The workings were extensive in the late 18th and 19th centuries, but today are obscured by modern industrial development. The stone is still seen in a wide variety of buildings, most notably in many of the much-restored churches of the north Nottingham suburbs e.g. St. Leodegarius, Old Basford and St Andrew's. Most are constructed of rock-faced, ashlared blocks of Bulwell Stone usually with quoins, mouldings and spire in paler, contrasting Lincolnshire Limestone. Bulwell Stone appears to have been a firm favourite of local Victorian architects and was used to good effect in St. Andrew's Presbyterian Church in Nottingham, with contrasting string courses of pale grey Lias and mouldings of Lincolnshire Limestone. It does not appear as a rule to have been used far outside the present City suburbs, but there are rare exceptions. St. Anne's Church at Radcliffe-on-Trent was built of yellow-brown Bulwell Stone, with grey skerry sandstone and Lias string courses, and buff Lincolnshire Limestone for all mouldings and carved work.

The Linby quarries supplied stone for Newstead Abbey in medieval times. Today they provide much of the material needed to conserve surviving Bulwell Stone buildings in the Nottinghamshire area. The stone was also used in many of the older villages near the quarries e.g. Linby village (Plate 1G) and at Annesley Hall and Church. Northwards, older houses at Kirby and Sutton-in-Ashfield are all built of locally quarried Cadeby limestones. Stone from the present Linby quarries can be seen in the newly built flood defence walls along the Trent at Wilford.

The local importance of the Cadeby Formation limestones for building is evident in other parts of this southern outcrop. The church at Strelley is built of a red-brown, highly ferruginous variety quarried within a hundred metres of the church. In general the more ferruginous varieties of the limestone, like the Strelley stone, appear to be less durable, and parts of the church fabric are severely decayed.

Farther north in the Mansfield area, the Cadeby Formation includes two sandy dolomitic limestone varieties known as the Red and White Mansfield stones. These are the only building stones from Nottinghamshire to have achieved any kind of national status in terms of their use and wide geographical distribution. Lithologically they are dolomitic limestones with a high quartz sand content (up to 50% siliciclastic sand grains) and are in consequence very durable. The limestones are commonly cross-cut by green grey clay seams similar to those seen in the Linby and Bulwell varieties. The Mansfield stones are good freestones, easily worked, and were therefore favoured for decorative carved work, such as is commonly seen in local churches and exemplified by the foliage carved on the capitals of the 13th century Chapter House of Southwell Minster.

These two Mansfield stones proved particularly popular with local builders and architects in the 19th century. Mansfield White is extensively use in Mansfield town, most notably for the town hall, but also in the large railway viaduct that dominates the town centre. Other examples include the 18th century town hall at Newark and pre-eminently the Norman Minster at Southwell. At nearby Mansfield Woodhouse the quartz sand content of the limestone has all but disappeared, but the stone was still widely quarried and there are many examples of its use in the older houses of the town (Plate 1H)

The Mansfield Red variety, now long worked out, was popular for decorative work. It was extensively used by the local Nottingham architect Watson-Fothergill in his 19th century city centre buildings, and is common as small, decorative columns in some of the larger Victorian villas of the Nottingham suburbs. It can also be seen in the large pillasters that front the 18th century Shire Hall (now the Galleries of Justice Museum). Elsewhere it can be seen in the quoins of the Castle Brewery, Newark, and was even used for a bank frontage in St Alban's in Hertfordshire. Nationally the stone was show-cased in the magnificent Midland Hotel at St Pancras, in London which was designed as a showpiece of the Midland Railway Company and built completely from materials obtained from quarries on the route of the line. The building includes Mansfield Red and Ancaster stonework, which contrasts with the red 'Gripper' bricks from the Mercia Mudstone brickpits of Mapperley in Nottingham. Originally the building also had a Swithland Slate roof, sadly replaced in later renovations by green Cumbrian slates. Perversely, the red sandstone used in Clumber Church was not the local Mansfield Red, but was Triassic sandstone imported from the Runcorn quarries in Cheshire by the Duke of Newcastle.

The earliest geological descriptions of the Mansfield Red quarries were provided by Sedgwick (1829). '*On the east side of the glen, which descends to Mansfield, is a quarry which lays bare a system of beds, about 50 feet thick, of very extraordinary character. The bottom beds are about 20 in number and vary from less than 1 to 3 or 4 feet in thickness; but the planes of separation are extremely irregular, and not continuous. They are of dull red colour, and might, without close examination, be mistaken for New Red Sandstone. The thin beds are much used in building, and the thickest are hewn out into large troughs and cisterns, and in that state are conveyed into all the neighbouring counties*'

In 1856 the first national survey of quarrying carried out by the Geological Survey listed three Mansfield building stone quarries owned by Charles Lindley (Hunt, 1860). The Mansfield Red Stone was then produced at '*9d per cube foot for random sized blocks.*' The average annual production of the quarry was '*5,000 cube feet*'. The stone was used in the '*Terrace at Trafalgar Square, also for altar steps, pavings etc., for interior of several churches. Large and small cisterns are made from this stone.*' The Mansfield White Stone was priced the same. The average annual production of this quarry was '*10,000 cube feet*'. The stone was used in the '*Town-Hall of Mansfield; several public and private buildings*' (Hunt, 1860). By 1861, three quarries were in operation at Chesterfield Road and Rock Valley (both owned by the Lindley family) and at West Hill, Chesterfield Road. Mr Gilbert Scott (subsequently Sir George Gilbert Scott), one of the principal architects of the Victorian period, described the Mansfield Stone as '*one of the best building stones in the kingdom*' (Aveline, 1861).

Stevenson (1866) refers to the Chesterfield Road red sandstone quarries of Mr William Sills and to quarries at Mansfield Woodhouse and Mansfield (Rock Valley Quarries). By 1930 there were nine building stone quarries in the Mansfield area, but only six were still active. The Rock Valley Quarries were then disused, and Lindley's White Mansfield was the major stone producer. Today the only survivor from this long tradition is the White

Mansfield Quarry (or Gregory Quarry), now owned by the Rare Stone Group.

North of Mansfield, most of the older houses and churches along the outcrop are constructed from Cadeby Formation limestones (e.g. Bolsover Castle, Welbeck Abbey, dressings of Thoresby Hall, Carlton in Lindrick, Worksop and Blyth priories and many village houses). The limestones, though dolomitized, have commonly retained much of their original fossiliferous fabric. They vary from white to pale yellow brown, and from finely crystalline to coarsely fossiliferous limestones. Houses in the Scrooby-Maltby area, close to the Yorkshire border, have been constructed from coarse-grained pisolitic lithologies. It is likely in the distant past that many different quarries were in operation supplying local building stone needs. However, by the early part of 20th century most quarries in the area were working the stone for crushed rock aggregate and lime rather than for buildings.

Cadeby Formation limestone is also extensively used in churches located beyond its immediate outcrop. In north Lincolnshire a lack of suitable alternative local stones has meant that the Cadeby limestones were extensively imported. Churches at Thurgarton, Retford, Clarborough, Gringley on the Hill, Walkeringham, and Misterton, each built of white Cadeby Formation limestone, provide typical examples. Several churches along the Humber Estuary have also used the limestone for their fabrics, e.g. at Barton on Humber. Cadeby limestone is also used with local Lincolnshire Limestone, ironstones and even some chalk block stonework in buildings in north Lincolnshire.

A number of large building stone quarries once operated in the Cadeby Formation close to the Nottinghamshire-Yorkshire border. These included the quarries adjacent to Roche Abbey (finely crystalline lithologies), at North Anston (bioclastic) and at Cadeby (oolitic and bioclastic). The quarries at Cadeby itself are still a major supplier of building stone for new buildings and for conservation work, including York Minster.

The Triassic rocks

The Palaeozoic rocks of the East Midlands area are succeeded eastwards and southwards by a thick, easterly-dipping Mesozoic (Triassic to Cretaceous) sequence. The Triassic red-beds consist of fluvial sandstones and non-marine mudstones. The succession in the East Midlands is subdivided into a lower unit of variegated sandstones with occasional pebbly horizons, the Sherwood Sandstone Group (formerly the Bunter sandstones and pebble beds), and an upper unit dominated by red mudstones termed the Mercia Mudstone Group (formerly the Keuper sandstones and marls). The upper unit also includes a basal sandstone unit, the Sneinton Formation, in the Nottingham area, and a series of thin but extensive sandstone beds (skerries) in its upper part. The recently revised Triassic litho-stratigraphy, is summarised in Table 5 (Warrington et al., 1980; Charsley et al., 1990).

In Nottinghamshire the Sherwood Sandstone Group is divided into the Lenton and Nottingham Castle Formations, neither of which have provided significant stone for building purposes (Table 5). The Nottingham Castle Sandstone Formation, despite its prominent exposure in the high cliffs below Nottingham Castle is too poorly cemented to produce durable block stone. However, the friable

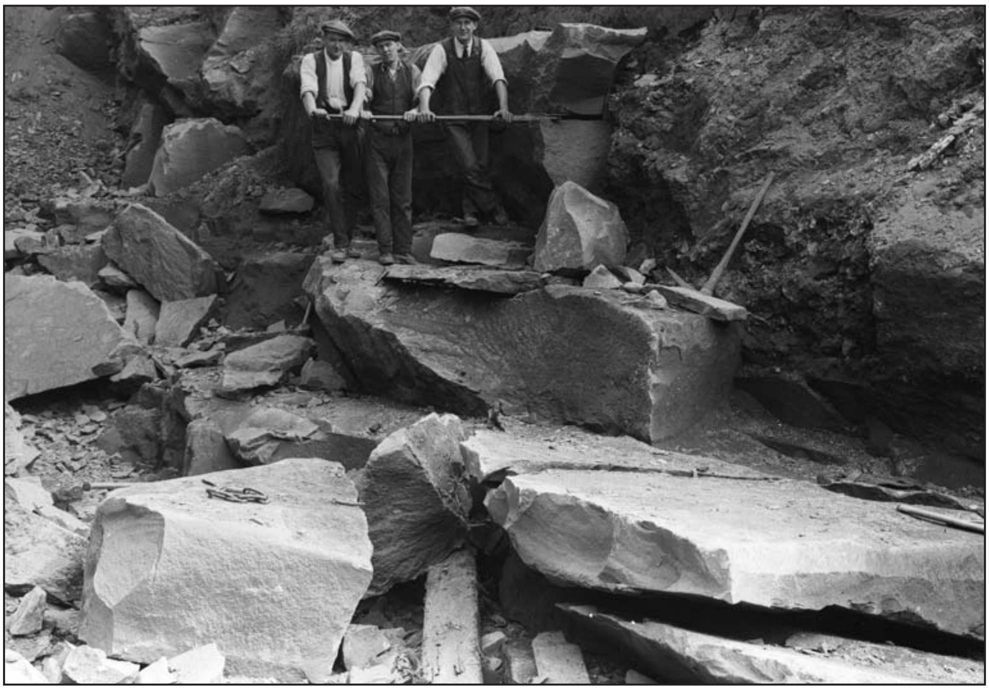


Figure 4. Lindley's Mansfield Red Quarry, at Mansfield: hand-working the dolomitic red sandstone of the Cadeby Formation. (BGS photo #A5053, 1930).

nature of the sandstones was exploited in other ways, notably to excavate the many caves and storage rooms that underlie the city centre of Nottingham (Waltham, 1996).

In south Derbyshire and Leicestershire, the Sherwood Sandstone Group is divided into three formations of which the youngest, the Bromsgrove Sandstone Formation (formerly the Lower Keuper Sandstone of Hull, 1869) is the only one of importance in terms of building stone production (Table 5). This has an outcrop extending from south of the Trent northwards towards Ashbourne and westwards into Staffordshire and Warwickshire (Fig. 1). The pale red to grey-green and occasionally the more highly prized white, sandstones were once extensively quarried for building in the area of Norbury, Cubley, Calke and Kirk Langley (Hull, 1869). Close to the Derbyshire–Staffordshire border, important building stone quarries have worked the Hollington Sandstone, also a part of the Sherwood Sandstone. These, and the Grinshill Quarries in Shropshire, are the only quarries still active in the unit, producing purple, red or mottled sandstones for buildings in Staffordshire and south Derbyshire (Craven and Stanley, 1982, 1984).

South of Derby, the Bromsgrove sandstones form an irregular outcrop around the margins of the Derbyshire-Leicestershire coalfield. They have been extensively worked in the past for local building stone at Repton, Bretby, Pistern Hill, Netherseal, Chilcote, Willesley and Alton Grange (Farey, 1815; Hull, 1869). Large quarries also operated along the Trent at Kingsmill and Castle Donnington and at Weston Cliff along the Leicestershire - Derbyshire border (Hull, 1869).

	Formation		Former Names		Building Stone Quarries
Mercia Mudstone Group	Blue Anchor				
	Cropwell Bishop		Keuper Marl	Siliceous 'Skerry' Sandstone	*Windmill 'Skerry'*
	Hollygate Sandstone Member Edwalton *Cotgrave Sandstone Member*				*Dane Hills Sandstone* *Hollygate 'Skerry'* Cotgrave 'Skerry'
	Gunthorpe			Dolomitic Skerry' Sandstone	*Plains, Maplebeck, Tuxford Laxton, Kneesall & Clarborough 'Skerries'*
	Radcliffe				
	Sneinton		Keuper 'Waterstones' Keuper Basement Beds		*Gedling* *Sneinton*
Sherwood Sandstone Group	Bromsgrove Sandstone	*absent*	Keuper Sandstone		*Weston Cliff* *Kingsmill* *Repton* *Norbury* *many local quarries*
	Polesworth	Nottingham Castle Sandstone	Bunter Sandstone		
	Moira Fm.	Lenton Sandstone			

Table 5. Triassic stratigraphy and building stone quarries of the East Midlands.

The basal sandstone unit of the overlying Mercia Mudstone Group is now termed the Sneinton Formation (formerly the Lower Keuper Sandstones or Waterstones). The Sneinton sandstones though relatively soft, were once an major source of building stone for Nottingham. Lithologically they are similar in character to the Bromsgrove sandstones, but are interbedded with subsatantial amounts of mudstones and siltstones. In the past, the two formations were mapped as one unit, the Lower Keuper Sandstones (Hull, 1869), but current stratigraphic practice places the Bromsgrove Sandstone in the Sherwood Sandstone Group and the more mudstone-rich Sneinton Formation in the Mercia Mudstone Group.

Bromsgrove and Sneinton building sandstones

Hull (1869) stated that 'the sandstones of the Lower Keuper Series are the most economically valuable of all which the Trias produces. In the central counties it is from them exclusively that the only good building stone can be procured'. The fine-grained, relatively soft nature of these sandstones, together with their occurrence in moderately thick beds, has meant they were a prime source of large ashlar block stone.

Sandstones from the Bromsgrove Sandstone Formation of South Derbyshire and Leicestershire were widely used in local churches and houses. They can be seen in houses at Castle Donnington (Plate 1I), Kingsmill and in churches at Hickling, Gotham, Radcliffe-on-Soar, Trumpton, Breedon on the Hill, Bunny and Keyworth. In south Derbyshire the Bromsgrove Sandstone was extensively used for larger houses either as block stone or as dressings for brick-built structures such as Sudbury Hall (Craven and Stanley, 1982). Further examples of its use for building include Calke Abbey, Elvaston Castle, and churches and houses at Bretby, Norbury, Cubley and Bentley. In these rural settings, without the discoloration caused by pollutants, the variegated greenish grey to reddish brown colours are more commonly seen in the building fabrics

The Sneinton Formation crops out along the south and east side of Nottingham but is only exposed between Sneinton and Gedling where it was quarried fairly extensively in medieval times (Charsley et al., 1990; Alexander, 1995). Little evidence of this quarrying survives, which are now large suburban housing estates. The greenish grey sandstones principally occur in church fabrics in the Nottingham area, where large, ashlared, sandstone blocks up to 1 m across and 0.3 m deep are commonly visible. Typically these fine-grained sandstones show prominent cross-bedding and convoluted soft sediment deformation structures. Clay pebbles or intraclasts are commonly present along the sets but are often eroded away to form small cavities in the blocks. The sandstone was particularly widely used for church tower and steeple construction, and outside the main urban areas has generally survived well (e.g. Gedling, Burton Joyce, Shelford, Epperstone churches). In the more polluted city centre sites, however, such as St. Peter's Church in Nottingham, the stone is considerably blackened. The Sneinton sandstones do not appear to have been used far from their outcrop area.

Skerry sandstones

Although the Mercia Mudstone Group is dominated by red-brown mudstone and siltstone it also includes, in its upper part, thin beds of hard, grey-green, fine-grained sandstone, known locally as skerries (Smith, 1910, 1913; Elliott, 1961). The term appears to be derived from the old Norse skaerr or Swedish skär meaning thin or fine (Arkell and Tomkieff, 1953). Its local use may therefore date from days of the Danelaw.

Stratigraphically the skerries can be divided into sandy (very fine-grained) dolomites in the lower part of the group and silica-cemented sandstones in the upper part (Lamplugh *et al.*, 1911). They range from isolated, discontinuous layers a few centimetres thick to more continuous and thicker sandstone beds that can be traced across much of the outcrop. In general the siliceous skerry beds are much more thinly developed than the dolomitic varieties. At some stratigraphic levels several beds may be concentrated into 'skerry belts', but individual sandstone units rarely attain more than 600 mm in thickness (Lamplugh *et al.*, 1911). An exception is the Dane Hills Sandstone in Leicestershire that may reach 7 m thick . In north Nottinghamshire, a unit of the 'skerry-rich beds', the Clarborough Beds, is also distinguished.

The dolomitic skerry comprise very fine, angular, silt-grade, quartz/feldspar grains in a microcrystalline dolomitic cement. The upper siliceous skerry beds have larger amounts of coarser detrital quartz and feldspar grains and a pervasive silica cement giving them an almost flint-like hardness. Common in many skerry sandstones are ripple marks and elaborate, convoluted, soft sediment deformation features – ball and pillow or flame structures. Exposed skerry surfaces commonly show cube-shaped moulds representing former halite crystals.

Skerry building sandstone

Beds of skerry sandstone crop out in the Triassic sequence throughout the East Midlands. Their occurrence within an extensive area of mudstone outcrop, which lacked a good alternative building stone, meant that in early buildings the skerry stone was widely used for rubble walling material including the Roman fort of Margidunum at East Bridgford (Oswald, 1927), the Bishops Palace at Southwell and village houses at Car Colston, Elston, Thurgarton and Maplebeck (Plate 1J).

Quarrying, or at least small-scale surface digging of the skerry sandstones has taken place all along the Trent valley at Hockerton, Tuxford, Laxton, Maplebeck and East Markham, but its widespread use in local buildings suggests that numerous other small pits were probably opened along the outcrop (Lamplugh et al., 1911). In these areas small, flat skerry stones commonly form debris in fields and would have been easily gathered for local building purposes. Although locally important, the skerry sandstones do not appear to have been used far from their outcrops.

Varitions in thickness and lithology of the skerries has meant that, in general, two types of stonework can be commonly identified in the buildings of the area. The thinner, siliceous skerry were generally too

Plate 1 (on following pages). Buildings of the East Midlands showing a selection of the wide variety of local building stones that have been used.

A. Osgathorpe, Leicestershire, 18C house; rubble walling of various Charnian lithologies.

B. Woodhouse Eaves, Leicestershire, 19C house; rubble walling and roofing slates both of variegated Swithland Slate.

C. Ashford in the Water, Derbyshire, 18C house; grey Monsal Dale Limestone with contrasting Millstone Grit Group sandstones for quoins and window surrounds.

D. Hognaston, Derbyshire, 18C house; Woodale Limestone with prominent dark chert bands.

E. Appleby Magna Moat House, Leicestershire, medieval; local Coal Measure Group sandstones.

F. South Wingfield, Derbyshire, 18C house; ashlar walling of local Wingfield Flags.

G. Linby, Nottinghamshire, 18-19C houses; Linby Stone from the nearby quarries.

H. Mansfield Woodhouse, Nottinghamshire, 16C and early 17C houses; slightly ferruginous limestones from the local Mansfield Stone quarries.

I. Castle Donnington, Nottinghamshire, 18C houses; large, greenish-grey, cross-bedded, ashlar sandstone blocks from the local Kingsmill Stone quarries.

J. St Radegund Church, Maplebeck, Nottinghamshire, medieval with later restorations; sandstone blocks of Maplebeck Skerry with soft sediment deformation structures.

K. Holwell, Leicestershire, 19C house; large blocks of ferruginous sandstone and ironstone of the Sandrock Member and Marlstone Formation.

L. South Scarle, Nottinghamshire, 18C house; yellow-brown and grey, coursed Lias limestone blocks.

M. Ketton, Rutland, 17C house; Colleyweston Slate roof, and Ketton Stone wall blocks.

N. Winterton, Lincolnshire, 18C house; small coursed blocks of locally quarried Lincolnshire Limestone.

O. St Mary's Church, Horncastle, Lincolnshire, medieval with later restorations; Spilsby Sandstone with original dressings and later inserted blocks of pale yellow Lincolnshire Limestone.

P. Wootton, Lincolnshire, 17-18C house; white Ferriby Chalk blocks with red brick quoins and tumbling.

A. Osgathorpe (Charnian) © G K Lott

B. Woodhouse Eaves (Swithland Slate) © G K Lott

C. Ashford-in-the-Water (Dinantian Limestone) © G K Lott

D. Hognaston (Woodale Limestone) © G K Lott

E. Appleby Magna (Coal Measures Sandstone) © G K Lott

F. South Wingfield (Wingfield Flags) © G K Lott

G. Linby (Linby Stone) © G K Lott

H. Mansfield Woodhouse (Mansfield Stone) © G K Lott

I. Castle Donnington (Kingsmill Stone) © G K Lott

J. Maplebeck (Maplebeck Skerry) © G K Lott

K. Holwell (Marlstone/Sandrock) © G K Lott

L. South Scarle (Lias Limestone) © G K Lott

M. Ketton (Colleyweston Slate) © G K Lott

N. Winterton (Lincolnshire Limestone) © G K Lott

O. Horncastle (Spilsby Sandstone) © G K Lott

P. Wootton (Ferriby Chalk) © G Lott

hard to cut and dress and are used for randomly coursed, rubble walling. They commonly form footings or part-walls to more substantial brick or timber framed buildings (in East Bridgford, Flintham, Elston, Diseworth). In contrast, the thicker skerry sandstone beds are softer and could be dressed into rough blocks (Coach and Horses Public House and houses at Thurgarton, and Kelham Church). Exceptionally large blocks were sometimes quarried from locally thickened beds, as can be seen in the church tower at Normanton-on-Trent. The Dane Hills skerry quarries, now lost in the suburbs of north Leicester, supplied pale grey sandstone block for much of the local area. A few remaining examples of its use include the Roman Jewry Wall and the nearby tower of St. Nicholas's Church in Leicester.

The Jurassic rocks

A prolonged period of marine sedimentation then followed the Triassic continental environments, and dominated deposition throughout the Jurassic and Cretaceous. Jurassic deposition commenced with the grey, calcareous mudstones, clay-rich limestones and yellow-brown to grey-green ironstones of the Lower Jurassic (Lias Group) (Table 6). Oolitic and shelly carbonate deposition characterises the succeeding Middle Jurassic succession that forms the pronounced high ground of the Lincolnshire Edge limestone escarpment, extending from the Humber Estuary southwards into Northamptonshire. A brief return to non-marine conditions was then followed by the re-establishment of fully marine conditions producing a mudstone-dominated Upper Jurassic succession, most of which is concealed beneath a cover of Pleistocene superficial deposits.

		Formation		Member		Building Stone Quarries
Upper		Spilsby Sandstone				See Table 5
	Ancholme Group	Kimmeridge Clay		'Elsham Sandstone'		locally quarried
		Oxford Clay				
		Kellaways				locally quarried
Middle	**Great Oolite Group**	Cornbrash				
		Blisworth		'Snitterby Limestone'		locally quarried
		Rutland				
	Inferior Oolite Group	absent				
		Lincolnshire Limestone	'upper'	Hibaldstow Limestone	numerous local quarries	*Hibaldstow* *Scawby* *Silver Beds* *Ancaster* *Wilsford* *Clipsham* *Heydour* *Casterton* *Stamford* *Ketton* *Colleyweston* *Wittering Pendle*
			'lower'	Kirton Cementstones Santon Oolite		
		Grantham				
		Northampton Sand				locally quarried
Lower	**Lias Group**	Whitby Mudstone				
		Marlstone Rock		'ironstone'	numerous local quarries	*Branstone* *Holwell* *Ab Kettleby*
		Dyrham		'sandrock'		*Wycombe* *Tilton*
		Charmouth Mudstone				
		Scunthorpe Mudstone		Foston	Frodingham Ironstone	locally quarried
			Blue Lias	Beckingham		
				Granby	'Granby Limestones'	locally quarried
				Barnby		
				Barnstone	Blue Lias 'limestones'	locally quarried
Triassic	**Penarth Group**	Lilstock		Cotham		locally quarried
		Westbury				

Table 6. Jurassic stratigraphy and building stone quarries of the East Midlands.

Within the Jurassic sequence there are various sources of building stone that have been widely exploited for local building. The 'Lias', notably in its lower part, is characterised by thinly interbedded, grey, argillaceous limestones and calcareous mudstones. Two locally developed, but lithologically distinctive, 'ironstone' dominated units occur – the 'Lower Lias' Frodingham Ironstone (Lower Sinemurian) and 'Middle Lias' Sandrock/Marlstone Rock (Pliensbachian). The Middle Jurassic succession of the East Midlands is divided into a lower interval termed the Inferior Oolite Group and an upper interval named the Great Oolite Group (Table 6). The Inferior Oolite comprises a lithologically varied sequence of ferruginous and calcareous sandstones, ironstones, oolitic and shelly limestones, silty limestones and occasional mudstones. The Northampton Sand and Lincolnshire Limestone (Table 4) are two of the major sources of local building stone.

Lower Lias building limestones

The pale grey to yellow-brown (when weathered), fine grained limestone beds of the Barnstone Member, formerly the Blue Lias (Table 6), were once a very important local source of building stone and appear in numerous older buildings in villages along the outcrop. From the 18th to early 20th centuries, these limestones also became the basis of an important hydraulic cement industry around Barrow-on-Soar, Barnstone, Granby, Cotham and Coddington (Woodward, 1893). These limestone beds extend across the whole of the East Midlands and beyond to Dorset, South Wales and the Yorkshire coast.

The large number and geographic extent of the surviving buildings constructed using these limestones suggests that quarrying was from a large number of small pits, most of which have long since degraded, but can still be seen, for example, in the valleys around Barrow-on-Soar and Widmerpool. The individual limestone beds are rarely more than 250 mm thick and need to be carefully selected because they do not weather well and in many instances tend to split (or shiver) along thin clay laminae. The limestone/mudstone sequence is commonly fossiliferous and was the source of the famous Barrow 'Kipper' (a 5 m plesiosaur skeleton). The thinly bedded, blocky nature of the limestone has meant that very little dressing or cutting was necessary to produce the small blocks used in wall construction. The limestones were also commonly used for wall footings, chimney stacks and internal floor slabs in some brick built houses of the area.

Good examples of Barnstone Member limestones in buildings can be seen all along the outcrop, in village houses, grand halls and parish churches at Barrow-on-Soar, Barnstone, Costock, Long Bennington, Staunton-in-the-Vale, Dry Doddington, Fenton, Collingham, South Scarle (Plate 1L) and Newark. Although these beds are no longer locally worked for building stone, there are several quarries producing comparable limestone from the basal Lias in Somerset.

Lower Lias building ironstones

The Lias Group succession of north Lincolnshire includes a thick localised deposit of grey-green (unweathered) to yellow-brown, commonly coarsely fossiliferous, calcareous, oolitic ironstone known as the Frodingham Ironstone (Member). Petrologically, the ironstones are generally highly calcareous with abundant shell debris, and distinctly oblate ooliths of berthierine (green iron silicate) and geothite set in a matrix of calcitic or muddy sideritic (Gaunt *et al.*, 1992). This ironstone unit, originally cropping out from Coleby southwards to the Ashby area, has been worked as a source of iron since Roman times. The ore formed the focus for the iron and steel industry that developed in the Scunthorpe area in the mid-19th century, and continues today. Long before this, however, the evidence of many churches and some houses in the surrounding area indicates that the ironstones were a locally important source of local building stone in earlier times. Around Scunthorpe, it is used as thinly bedded blocks, characterised by abundant large Gryphaea, in many local houses and churches, notably at Scotter, Messingham and Bottesford (Scunthorpe). St John the Evangelist Church in Scunthorpe is a fine example of the use of dark brown, coarsely fossiliferous and oolitic Frodingham Ironstone, with pale 'streaky' limestone (probably from Ancaster) as dressings.

Middle Lias building ironstone

'Ironstones' clearly form some of the more distinctive of the region's vernacular building stones. Those of the Middle Lias Marlstone, though superficially similar to the Frodingham ironstones, include a wider range of lithologies, with fossiliferous and ferruginous sandstones, limestones and oolitic ironstones. The names that once described this 'iron-bearing' succession, of the Leicestershire-Lincolnshire area have changed many times since the earliest research 200 years ago (Table 6). Traditionally, the Marlstone was divided into an upper unit of iron-rich beds, the 'ironstone' proper, and a lower unit of ferruginous sandstones, known as the Sandrock. Together these units formed the Marlstone Rock Bed. Recent mapping by the BGS, together with a better understanding of regional stratigraphic relationships (Berridge *et al.*, 1999) now places the lower Sandrock beds into a newly defined unit called the Dyrham Formation (formerly the Middle Lias Silts and Clays). The 'ironstone' beds alone, therefore, comprise the whole of the unit now termed the Marlstone Rock Formation. Petrologically the Marlstone Rock ironstones are sideritic-berthierine (chamositic) limestones. Siderite (iron carbonate) and berthierine (a green, iron-silicate), both oxidise to yellow-brown limonite/geothite during weathering. The ironstones contain abundant fragmental shelly material and sporadic fossiliferous horizons. Fresh ironstone blocks are commonly termed 'blue-hearted' where the core of the block has been protected from weathering and oxidation effects.

The widespread use of both the Sandrock and Marlstone Rock stones in the fabrics of older buildings all along the outcrop indicates that quarrying of the stone for building purposes was once extensive. Although this activity has a long history, little is known about this early quarrying industry. Building stone was probably obtained from a large number of local pits or quarries and some may even have been opened to supply stone for a single structure. Unfortunately, subsequent workings for iron ore, in the late 18th and early 19th centuries, have removed most traces of earlier building stone quarries, but local names such as Stonepit Spinney, near Ab Kettleby, give some clue as to their possible locations. There is also documentary evidence that 'ironstone' beds were quarried for building stone at Branston, Holwell, Wycomb, Ab Kettleby and Tilton (Woodward. 1893).

Quarrying of the ironstone as an ore dates from about 1856, but the real expansion in the industry accompanied the development of local rail networks, enabling the ore to be shipped to existing smelting furnaces in Yorkshire and Derbyshire. Local furnaces, such as those at Asfordby, were not established until as late as 1881 (Wright, 1982).

The highest grades of ore come from the Marlstone Rock Formation. As building stones, however, these darker, red-brown stones, though locally common in some wall fabrics, are in general less durable and were rarely used. The harder, yellow-brown, ferruginous and calcareous sandstones of the underlying 'Sandrock' have generally been preferred for building (Lamplugh *et al.*, 1920). They are well displayed in the walls of Belvoir Castle and Harlaxton Manor, and also in houses and churches in numerous villages along the outcrop, including Wartnaby, Ab Kettleby, Holwell (Plate 1K), Barrowby, Redmile, Marston, Barkston, Easton, Muston, Oakham, Lyddington and Belton-in-Rutland. The local buildings commonly include some particularly distinctive stone blocks containing concentrations or ‘nests’ of fossil brachiopod shells (Hallam, 1961). These shelly beds were described by the quarrymen as ‘jacks’ and provided harder, very well-cemented building blocks which are commonly seen to stand proud in the weathered wall fabrics. In Caythorpe, in Lincolnshire, ‘ironstone’ is decoratively interbanded with paler Ancaster Stone in the walls of the buildings.

The sandstones and ironstones have been used both as irregularly shaped rubble stone and as squared, cut ashlar block in the local buildings. They are only rarely used for carved stonework because they are generally too soft, but are occasionally used in window and door mouldings as in the church at Eaton-on-the-Hill. In most instances pale, buff-coloured oolitic and shelly Lincolnshire Limestone ashlar blocks were preferred in such situations where greater strength was required. This contrast between the local yellow-brown ironstone wall fabric and quoins, window and door surrounds in the paler Lincolnshire Limestone is a characteristic feature of the buildings in the area.

Today there are no quarries producing ironstone in the local area, and recent conservation work has to rely on replacement stone from the ‘Marlstone Rock’ quarries at Hornton and Wroxton in the South Midlands or from the Northampton Sand Formation (Middle Jurassic) in Northamptonshire.

Northampton Sand building stones

The orange-brown to green-grey, ferruginous Northampton Sand Formation, with its outcrop from Lincoln south to Towcester, is widely used for building stone throughout Northamptonshire (Hudson and Sutherland, 1990). The formation is very poorly developed north of Grantham, but to the south was commonly quarried for building purposes and can be seen in local houses and churches. The Marlstone Rock Formation also crops out in this area and, as these two units yield building stones similar in colour and lithological character, they need to be carefully distinguished.

The Northampton Sand Formation was formerly quarried for building stone around Barnsdale, Whitwell and Uppingham. Buildings along the main street of Uppingham have fine and varied examples of the use of this local ironstone. Along with Barrowden and Glaston, Uppingham also has houses with polychromatic interbanding of the Northampton ‘ironstone’ with paler Lincolnshire Limestone.

Lincolnshire Limestone building stone

In the whole East Midlands the most important sources of building stone are the upper and lower divisions of the Lincolnshire Limestone Formation, which have been worked since Roman times (Table 6). The formation is restricted to the East Midlands with a continuous outcrop from Kettering to just north of the Humber (Sylvester-Bradley and Ford, 1968; Ashton, 1975). It comprises a lithologically diverse succession of pale yellow, cream, reddish or buff limestones (when weathered) which are blue-grey or blue-hearted when freshly quarried from beneath the weathered zone. The limestones may be coarsely shelly, oolitic or finely micritic and silty in character. They have been extensively worked for building stone under a plethora of local quarry names, including: Weldon, King’s Cliffe, Barnack, Colleyweston Slate, Wittering Pendle, Ketton, Edith Weston, Stamford, Casterton, Clipsham, Heydour, Ancaster, Cathedral, Hibaldstow, Newbold and Cave Oolite. Most of the older buildings in villages along the outcrop, the ‘Cotswolds’ of the East Midlands, are constructed of Lincolnshire Limestone. Houses and cottages of lower status are commonly constructed of uncoursed rubblestone while the more substantial houses are built of finely cut ashlar block. It is likely that the rubblestone was obtained from numerous local pits whereas the sawn, ashlared stones were probably supplied by a few better established local quarries.

The most famous and productive of the many quarries in the region were those in the Stamford and Ancaster areas. South of Stamford, the famous Colleyweston ‘slates’ have been worked for centuries from the lowermost silty limestone beds of the 'lower' Lincolnshire Limestone. At the Neville Holt inlier, near Medbourne, Leicestershire, beds equivalent to those found at Colleyweston were also quarried for roofing slate. The characteristically graded roof of Colleyweston-type slates, largest at the eaves and smallest at the ridge, is still a common sight in the villages of the Leicestershire-Lincolnshire border area (Plate 1M) (Walton, 1975). This lower unit is also the source of the Wittering Pendle, a compact buff, silty (siliceous) limestone variety that was widely used in and around Stamford for building purposes and can be distinguished by its thinly bedded courses (Ireson, 1986).

The more massively bedded, oolite-dominated limestone succession of the 'upper' Lincolnshire Limestone has been extensively quarried at Ketton, Casterton, Ponton and Clipsham. The Ketton Quarries produce what has been described as Britain’s most ‘perfect’ freestone (Arkell, 1947). No other Jurassic limestone in Britain, with the possible exception of some beds of Casterton Stone, shows the same well-sorted, fine-grained, oolitic structure. The fine, even-grained fabric has meant that the stone has always been sought after for the most delicate decorative carving on buildings and tombstones.

Throughout the earliest history of the quarries (16-18C), Ketton Stone was mainly taken south to markets at Cambridge and beyond, and is rarely seen in the East Midlands (Purcell, 1967; Best *et al.*, 1981). By the 19th century, improvements in transport saw a more widespread use of the stone, notably for conservation work, as in Westminster Abbey, the Palace of Westminster and Ely Cathedral. Locally it can be seen in the quoins and decorative mouldings of St. Bernard's Abbey in Charnwood Forest, where it contrasts with the dark Charnian rocks of the main wall fabric.

Although the Ketton Stone is distinctive, the other 'upper' Lincolnshire Limestones are less easily distinguished one from another. The quarries in the Barnack area produced block stone which appears to vary from a distinctive hard, coarsely shelly variety (ragstone), which was widely used, for example in the 'long and short' Saxon stonework of Barnack church and in some of Stamford's churches (Dawn, 1993), to finer, more even-grained, oolitic and shelly block stone. Stone from the King's Cliffe quarries appears to show similar variations in character and relating the provenance of the stones to individual quarries therefore relies largely on documentary evidence (Purcell, 1967). The importance of the Barnack quarries, particularly for ecclesiastical buildings (Ely and Peterborough cathedrals; Crowland, Sawtry, Thorney and Bury St. Edmunds abbeys) has been documented by Salzman (1967), Jope (1964), Purcell (1967) and Ireson (1986). Perhaps the pre-eminent examples of the use of stone from the quarries near Stamford is the Norman Cathedral at Ely (Barnack Stone, with modern Clipsham restorations) and the 16th century Burleigh House (King's Cliffe, Barnack and other stones) (Eric Till, *pers comm.*, 1995). Further afield, the famous 15th century 'Stump' of St Botolph's parish church in Boston was built of coarse shelly and oolitic Lincolnshire Limestone, probably sourced from the Barnack area.

North of Stamford the 'upper' Lincolnshire Limestone is still worked in large quarries at Clipsham. Here the limestone may be coarsely shelly, peloidal or oolitic in character depending on the beds being worked. The quality, durability and availability of the Clipsham Stone has meant that it has been widely used to replace weaker limestones in many historic structures. A prime example is the Houses of Parliament, where many of the original magnesian limestone (Cadeby Formation) blocks from the Anston Quarries of south Yorkshire, have decayed badly and been replaced using Clipsham Stone. Though texturally and petrographically different, it is durable and reasonably similar in colour. Many other examples of replacements by Clipsham Stone, not always to the best advantage, occur throughout England, including Windsor Castle (14C); more recently Ely Cathedral, Eton College, York and Southwell Minsters and extensively, in the last century, colleges at Oxford (Arkell, 1947).

Farther northwards along the outcrop in the Wilsford-Ancaster-Leadenham area the 'upper' Lincolnshire Limestone has been worked as a freestone since Roman times (Purcell, 1967; Alexander, 1995). In most of the villages along this part of the outcrop, including Ancaster, Fulbeck and Leadenham, limestone is used almost exclusively in the older buildings. At Caythorpe the limestone is used with contrasting courses of ironstone from the Marlstone Rock Formation. Most of the impressively tall church spires, for which Lincolnshire is justly famous, were built of Lincolnshire Limestone, much of it from the quarries of the Ancaster-Wilsford area; these incude spires at Grantham, Brant Broughton, Louth, Newark and Bottesford.

Lincolnshire Limestone was very much the stone favoured for the great country houses of this part of the East Midlands. Belton House (late 17C) was constructed of Lincolnshire Limestone from quarries at nearby Heydour, while Wollaton Hall in Nottingham (late 16C) is documented as built of Ancaster Stone. Most villages along the outcrop have smaller halls or manor houses built of locally quarried Lincolnshire Limestone; Sudbrook, Caythorpe and Leadenham Halls are just a few such examples.

North of Ancaster, the limestone edge which dominates Lincoln has been quarried to provide

Figure 5. Thompson's Ancaster Stone Quarry, Wilsford Heath, Ancaster, with 4.5 m of Rutland Formation clays and sands overlying thickly bedded Ancaster Stone of the Lincolnshire Limestone (BGS photo #A6333, 1933).

stone for the Norman castle and cathedral and presumably for many lesser properties in old Lincoln such as the 12th century Jew's House. The original quarries, aptly named Dean and Chapter or Cathedral quarries, have remained under the control of the cathedral authorities and are still extant. They lie within the city limits close to the cathedral and work the limestone unit, known locally as the Silver Beds, from the 'lower' Lincolnshire Limestone (Jefferson, 1992). The limestone is typically a grey to buff, variably oolitic and shelly limestone, and is still primarily used to maintain the fabric, despite a brief dalliance with less durable foreign limestones.

When traced further along the crop into north Lincolnshire the oolitic and shelly nature of the limestones begins to change. In the Kirton in Lindsay and Hibaldstow areas a lower interval of oolitic limestone, locally termed the Santon Oolite Member, has been quarried for local building stone, together with the overlying fine-grained, micritic limestones of the Kirton Cementstone and Hibaldstow members. The main oolitic beds, characteristic of the 'upper' Lincolnshire Limestone farther south, are much reduced in this area where they are known as the Hibaldstow Beds. The fine, even grained oolite has been quarried for freestone and its use can be seen in houses in Redbourne, Hibaldstow and most notably at Winterton (Plate 1N). Northwards, across the Humber, the equivalent limestone unit is known as the Cave Oolite, which has also been widely used as a local building stone.

Great Oolite Group building limestones

Unlike the equivalent beds in southern England, which include the thick oolitic limestone developments of Bath and the Cotswolds, the Great Oolite Group of Lincolnshire and Leicestershire is a relatively thin, fine-grained, clastic sequence of sandstone and mudstone with only poorly developed limestone beds. It is divided into three formations, Rutland, Blisworth and Cornbrash, that only have local significance as building stone sources (Table 6).

The sandstone beds are generally too poorly cemented to have had any importance as a building stone. The thin pale grey, micritic, fossiliferous and non-oolitic limestones have, however, been worked for building stone in some localities. These limestones are the equivalent of the Blisworth Limestone (Table 6) which is developed and used as a building stone in the Northamptonshire area (Hudson and Sutherland, 1990). A thin development of the limestone extends into south Lincolnshire, but the presence of easily accessible quarries in the Lincolnshire Limestone has reduced its importance as a building stone. The equivalent bed in north Lincolnshire is a flaggy, fine grained limestone known as the Snitterby Limestone, which had limited local use for building and rough walling in villages close to the outcrop, including Snitterby and Waddingham (Gaunt *et al.*, 1992).

The thinly developed Cornbrash Formation, marking the top of the Middle Jurassic succession, is a fossiliferous limestone known to have been used for rough building work north of the Humber at South Cave (Gaunt *et al.*, 1992). No unequivocal examples of its use have been observed along its Lincolnshire outcrop.

Upper Jurassic rocks

The thickly developed but poorly exposed Upper Jurassic succession of the East Midlands is dominated by mudstones and siltstones, and is termed the Ancholme Group (Table 6). The group, which includes the Oxford and Kimmeridge Clay formations, has been worked locally for brick clay, but seldom for building stone. The possible exceptions are the thin basal sandstone beds of the Kellaways and the locally developed Elsham Sandstone, within the Kimmeridge Clay. No unequivocal examples of the use of Kellaways 'sandstone' have yet been found in the area. The Elsham Sandstone, however, has a moderately thick development around Elsham where it has been has been quarried. The local church and houses possibly include Elsham Sandstone in their fabric, but petrographic study is needed to confirm this.

The Cretaceous rocks

In the steep-sided valleys of the south Lincolnshire Wolds, the oldest rocks of the marine Cretaceous succession are exposed. They comprise a basal sandstone unit, the Spilsby Sandstone Formation, which spans the Jurassic-Cretaceous boundary, and a thin but lithologically and stratigraphically complex succession of interbedded sandstones, mudstones, ironstones and limestones (Table 7). Capping the valley sides and forming a second escarpment, are the white chalks of the Upper Cretaceous succession (Table 8), extending from the Humber coast southwards to the Wash and continuing eastwards offshore beneath the southern North Sea. Chalk is only well exposed along the edge of the escarpment, and the long dip-slope to the east is largely masked by thick Pleistocene deposits. The Cretaceous beds have yielded a few building stones for local use, but none has been distributed beyond the outcrop area.

Lower Cretaceous building stones

As with other successions in the East Midlands area, only the harder, well-cemented beds within the sequence have been worked for building stone, and each appears to have its own local sphere of influence. The basal sandstone unit, the Spilsby Sandstone Formation, crops out only in south Lincolnshire but, based on its widespread occurrence in local buildings, was probably the most important of the Cretaceous building stones of the area. The Spilsby Sandstone is a poorly cemented, greenish grey, ferruginous, fine-grained, spordically pebbly, glauconitic sandstone. It was once extensively worked for building stone along the Calceby Beck at Salmonby, Ashby Puerorum and Harrington Carrs (Jukes-Brown, 1887). Churches, farm buildings and the lowermost stone courses of many buildings in the villages around this quarrying area are built of this sandstone. Despite its relatively soft nature it was evidently widely favoured for building purposes and can be seen in churches at Horncastle (Plate 1O), Fulletby, Tetford, South Thoresby, Alford, Cumberby, Donnington on Bain, South Willingham and as far north as Grimoldby. There are no quarries working the sandstone today, posing a problem for the conservation of the many buildings made of it. There are many cases where unsuitable stones, such as buff Lincolnshire Limestone have been inserted into the green sandstone fabric.

Farther north in Lincolnshire, the Spilsby Sandstone is gradually replaced by ironstone as the principal building stone. The ironstone mainly used comes from the Lower Cretaceous Claxby Ironstone Formation (Table 7). This is commonly pale yellow-brown but may include orange-brown to purple-red varieties. It is a muddy, calcareous ironstone, sparsely oolitic and often with large thick-walled bivalves (Gaunt *et al.*, 1992). The ooliths are distinctly spheroidal and ferruginous, often giving the rock an 'ironshot' appearance. The ironstone has been exploited as an ore since Roman times (Squires and Russell, 1999) but was also widely used in buildings along its outcrop at Claxby, Market Rasen, Cadney, Ulceby, Swallow, Cuxwold, Rothwell and Caistor. Cottages in the picturesque village of Nettleton are mainly built from the local Claxby Ironstone.

	Stage	Formation	Member	Previous Terminology	Building Stone Quarries
Upper Cretaceous	Cenomanian	Ferriby Chalk		Red Chalk	
Lower Cretaceous		Hunstanton Chalk			
	Albian	Carstone Grit		Carstone	
	Aptian	'Sutterby Marl' 'Skegness Clay'		Sutterby Marl Skegness Clay	
	Barremian	Roach		Fulletby Beds	
		Tealby	Upper Tealby Clay	Tealby Beds	
			Tealby Limestone		*Locally quarried at Tealby*
	Hauterivian		Lower Tealby Clay		
		Claxby Ironstone	Upper Claxby Ironstone	Claxby Beds	*Claxby*
	Valanginian		Lower Claxby Ironstone		
	Ryazanian	Spilsby Sandstone	Upper Spilsby Sandstone	Spilsby Sandstone Beds	
Upper Jurassic	Volgian/ Portlandian		Lower Spilsby Sandstone		*Salmonby* *Ashby Puerorum* *Harrington Carrs*

Table 7. Lower Cretaceous stratigraphy and building stone quarries of the East Midlands.

The Tealby Formation, which overlies the Claxby Ironstone, is a sequence dominated by mudstones, with a thin and distinctive grey, micritic limestone, the Tealby Limestone Member, which crops out only in the Tealby-Walesby area (Gaunt *et al.*, 1992). It has been used as a rough walling stone in Tealby village.

A return to more ferruginous lithologies occurs in the succeeding Roach and Carstone formations. The thin, calcareous, fossiliferous sandstone and oolitic ironstone unit known as the Roach Formation is variegated in colour, ranging from greenish grey to yellow-brown in its more weathered state. The Roach is similar to the overlying ferruginous Carstone beds, making their identification difficult. The Roach Formation outcrop is restricted and as yet no examples have been unequivocally identified of the stone being used for building, despite its local potential.

The Carstone Formation represents a final phase of clastic deposition before the onset of Upper Cretaceous chalk sedimentation. This yellow-brown, fine to coarse, pebbly ferruginous sandstone is thinly developed over most of the area and unconformably overlies earlier formations (Gaunt *et al.*, 1992). It has been used extensively for vernacular building south and east of the region in Norfolk (Gallois, 1994) and around Ely (Ashurst and Dimes, 1990) but it is not seen in buildings in Lincolnshire, perhaps because of its softer, more friable nature.

Upper Cretaceous building stones

A thick succession of fine-grained, white to pale grey, chalky limestones, now termed the Chalk Group, constitute the Upper Cretaceous rocks of the area (Table 8). The basal interval of the chalk succession, is characterised by a distinctly reddened chalk lithology interval, the 'Red Chalk' or Hunstanton Formation. These red chalks have been extensively used for vernacular building stone near the outcrop in north Norfolk, but lack of suitable exposure of the unit appears to have precluded its use in Lincolnshire.

The overlying white chalk succession, has an outcrop extending from Norfolk across the Lincolnshire Wolds into Yorkshire and is subdivided into four lithostratigraphic units (Wood and Smith, 1978). Within Lincolnshire only the three lower divisions are known to occur, namely the Ferriby, Welton and Burnham formations (Table 8). Of these only the Ferriby and Welton formations can be seen at outcrop as the Burnham Formation is buried beneath a thick cover of Quaternary deposits. Perhaps an unlikely source of building stone at first sight, chalk lithologies, particularly the harder beds, are widely used in the area (Judd, 1867). It is also notable that across the Humber, in the Wolds of East Yorkshire, vernacular chalk buildings were once a very common feature and many examples still survive (Hayfield and Wagner, 1998).

The chalk of the Lincolnshire Wolds is typically white to off-white, very fine-grained and hard. Chalk blocks are used in a number of buildings across the outcrop, most notably including the remnants of the 12th century Louth Abbey and Legbourne church. The rock at outcrop around Louth is part of the Ferriby Chalk, and a hard unnamed chalk interval, stratigraphically equivalent to the better-known Totternhoe building stone of Cambridgeshire, is believed to have been the principal stone source (Judd, 1867).

Farther north along the outcrop there are many examples of chalk being used for local building stone both in external and internal walling. Farm buildings at Elsham and older houses at Croxton and Wooton are built of a colourful mix of squared chalk blocks with red brick quoins (Plate 1P). The church at Horkstow is constructed entirely of ashlar chalk, and in the abbey ruins at Thornton internal walls were at least in part lined with chalk blocks, some of which have large grey flints still embedded in them. Some quoins of chalk buildings are blocks of the Claxby Ironstone that have weathered quite badly.

	Stage	Formation		Building Stone Quarries
Upper Cretaceous (Chalk Group)	Santonian	Upper Chalk	Flamborough Chalk (flintless)	*(not exposed at surface)*
	Coniacian		Burnham Chalk (with flints)	
	Turonian	Middle Chalk	(with flints)	*Thornton*
	Cenomanian		Welton Chalk (flintless)	
		Lower Chalk	Ferriby Chalk (flintless)	*Ferriby* *Louth*
	Albian	Hunstanton Chalk (red chalk)		

Table 7. Lower Cretaceous stratigraphy and building stone quarries of the East Midlands.

The Upper Cretaceous Chalk successions south of Lincolnshire were important sources of flint, and flint-faced buildings are common throughout Norfolk, Essex, Kent and Sussex. The siliceous flints, which in their best-known natural form are irregularly shaped nodules, were used either as rubble-fill for walling or were carefully broken and shaped (knapped) for wall facings. The black flint varieties were particularly sought after for this latter purpose. Although flint is common in some parts of the succession across the Lincolnshire Wolds (Mortimore and Wood, 1983), there appears to be little evidence of its use as a building material. Of the few examples of flintwork seen in the area, the best known is the flint-faced church at Sutton Bridge, close to the Lincolnshire-Norfolk boundary. The reason for this lack of use is not clear, although it is evident that the character and form of the Lincolnshire flints, which commonly occur as large tabular masses, differ from the nodular varieties of the southern Chalk outcrops. The Lincolnshire flints are typically pale grey and lie within a harder chalk matrix, and it may be that the hardness of the matrix was also a deterrent to the development of a local flint mining industry.

Quaternary building stones

Extensive tracts of unconsolidated Pleistocene fluvio-glacial sediments (sands, gravels, glacial tills and clays) blanket much of the ground over the eastern part of the region, particularly along the main river courses. Although appearing an unlikely source of building stone there are in fact several sites in the area where larger, lithologically varied pebbles and cobbles from these deposits have been used to provide a utilitarian walling material. Good examples include the Anglo-Saxon churches at Waithe, Holton le Clay, Scartho and Clee (the latter three with Claxby Ironstone). Wall fabrics at Wysall and Stanton on the Wolds churches also include cobbles from the local fluvio-glacial deposit.

Another distinctive Quaternary building stone in some parts of the East Midland area is calcareous tufa (or travertine). The tufa is precipitated as calcium carbonate around springs discharging from limestone and was originally found on many of the limestone areas of the East Midlands. As a building material it has a long history. It was particularly favoured by the Romans, perhaps because of its common usage in many important buildings in Rome itself, and later was much prized by Norman builders. It is easily worked, strong, highly porous and therefore light. These properties made it a suitable choice for use in vaulting of churches and

Figure 6. Marl Cottage, Via Gellia Valley, Derbyshire, constructed of large blocks of calcareous tufa quarried from the hills behind (BGS photo #A9125, 1957).

cathedrals. Tufa from the Carboniferous limestones of Derbyshire has been used on a small scale in walls and buildings in Derbyshire, most notably in Marl Cottage beside the Via Gellia road (Fig. 6). Thick deposits formerly occurred around Matlock Bath, where it was commonly used as walling stone, and extensive deposits are still found in Lathkill Dale and Monsal Dale (Pedley, 1993; Pentecost, 1999). Tufa deposits have been recorded on the Jurassic and Cretaceous limestone outcrops of the area but there is no evidence that any of the accumulations were large enough for significant exploitation as building material (Gaunt *et al.*, 1992).

Overview

The primary source for information on the early history of the building stone industry lies in the correct geological identification of the stones used in surviving buildings, and then matching them with potential quarry sources. Sometimes this process may be simplified by access to documentary evidence; however, this is usually only available for high-status buildings, principally those constructed by the Church or Crown. Alexander's wide-ranging study (1995) of major medieval buildings in the East Midlands, including Lincoln, Peterborough and Ely Cathedrals and Southwell Minster, has provided numerous examples, mainly from the 11th to 15th centuries, where documents detailing their construction can be used to establish the location of many early East Midlands quarries. Her work, following the trail blazed by Knoop and Jones (1933, 1938), Arkell (1947), Saltzman (1967) and Purcell (1967), has provided yet more evidence of the importance of the Lincolnshire Limestone quarries in particular to both the early building history and economy of the East Midlands area. However, documents are commonly incomplete or provide ambiguous data, in which case the researcher must turn to geology to identify the stones.

The smaller stone-built vernacular houses, of which the East Midlands still has many, rarely provide useful documentary evidence and correct geological identification of the stone becomes the only viable starting point. The precise provenance of every stone is not always identifiable, as stone can vary significantly in character from bed to bed and quarry to quarry. Problems may also arise where, over time, the names of some stones, such as *Mansfield* or *Barnack*, because of their quality and reputation, were applied indiscriminately to quarries which had no real link to the original stone source. It should however be possible to recognise most stones in the smaller buildings of the East Midlands to at least a generic level (e.g as Charnian rocks or Lincolnshire limestones), and it is hoped that this article goes some way to providing the data to make such identifications.

A factor of considerable importance to understanding where building stones were quarried and how they were distributed is the development of transportation networks. The majority of the East Midlands quarries were up until the end of the 18th century, only able to supply local building needs. Heavy and bulky stone could not easily be moved by cart or packhorse even after the establishment of the first metalled turnpike roads. Successful early quarries were, therefore, those situated near a navigable waterway or near the coast. Good examples were the Lincolnshire Limestone quarries at Stamford, Ancaster and Lincoln, which all developed their access to navigable rivers as far back as Roman times. The Barnack quarries used the Nene and Welland rivers to supply building stone to south Lincolnshire, Norfolk and Cambridgeshire (Purcell, 1967; Alexander, 1995). The Lincoln and Ancaster quarries could send stone both west to the Trent via the Fossdyke canal and east to the coastal port of Boston via the River Welland.

In Leicestershire and Nottinghamshire, the early quarries at Repton, Weston on Trent and Kingsmill could use the Trent to supply the Triassic sandstones to the many medieval churches along its banks, such as at Barton-in-Fabis, Thrumpton and Ratcliffe-on-Soar. In north Derbyshire and south Yorkshire, Carboniferous sandstone quarries used the rivers Trent and Don as links to the Humber, allowing wider distribution of their millstones and other stone products. Mountsorrel granodiorite and Swithland slates were despatched via the River Soar.

From the end of the 18th century the development of the canals network transformed the stone industry by offering a relatively inexpensive means of transport. A useful overview of stone transportation and its costs was provided for the early part of the 19th century by the survey to identify stone sources for the new Palace of Westminster, built in 1839-1852 (Barry *et al.*, 1839). In this nationwide survey of 102 building stone quarries, the proposed mode and cost of transport to London were described and several quarries from the East Midlands were included (Table 9). Those eventually selected included Mansfield White and Bolsover, but most of the construction was carried out using Anston Stone from just over the border into South Yorkshire. Transportation of stone from the North Anston quarry was via the nearby Chesterfield Canal to the rivers Trent and Humber and then by sea to London (Lott and Richardson, 1997).

Quarry	**Probable transportation route**	**Cost** (quarry)	**Cost** (London)
Ancaster	By land to Grantham; by canal to Boston and by sea to London (*with no canal from Grantham to Boston this is surprising*).	9d	2s 6d
Barnack Mill	By land to Wansford, canal to Sutton Bridge, and then by sea to London	1s	2s 3d
Bolsover	By land to Chesterfield Canal at Worksop; by canal to Stockwith; by the Trent and sea to London	10d	2s
Cadeby	By land to the Don Navigation; on to Thorne and the Ouse/Humber; by sea to London	not given	1s 10d
Duffield Bank	Not specified	1s 1d *	not given
Dukes	By canal to Leicester (*unspecified*); by Grand Junction canal to London	7d	2s 8d
Haydor (Haydour)	By land to Sleaford; through Boston by sea to London	8d	2s 4d
Hopton Wood	By land to Cromford wharf; by canal to London (*unspecified*)	3s to 4s	4s 10d to 5s 10d
Ketton	By land to Stamford; to London via Wansford? (*unspecified*)	1s 9d	3s 4d
Lindrop	By land to Cromford Canal; by canal (*not specified*) to London	not given	not given
Morley Moor	By land to Little Eaton; by canal (*unnamed*) to London.	10d	not given
Mansfield White and Red (Lindley's)	By land to railway wharf at Mansfield; to Pinxton by rail; to Gainsborough by boat using the Trent and Irwash and then by sea, *presumably via the Humber*, to London	8d	2s 2d to 2s 6d
Shaw Lane, Belper	*Not specified*	1s 1d *	not given
Stancliffe Darley Dale	By land to Cromford; thence to London (*route unspecified*)	1s 5d	3s 3d

Table 9. Potential building stone sources for the Palace of Westminster (after Barry, 1839). Costs are per cubic foot, at the quarry and delivered to London. s = shillings, d = pence. * costs for white stone; stone that was half brown and half white cost 9d.

With the development of the national rail and road systems, particularly in the second half of the 19th century, the building stone quarrying industry expanded dramatically. In the East Midlands, the Carboniferous sandstone quarries of Derbyshire developed into a major national resource and supplied stone to most major cities. The downside of this expansion was of course the decline in the need for smaller local stone quarries, and coupled with the expansion of the brick industry, quarrying of the many vernacular stones of the area ceased to be an economic proposition even for local markets.

Today's stone industry in the East Midlands is mainly concentrated along the Derwent valley, but with small but important production remaining around Ancaster and Stamford. Many stones are now no longer produced. There is no current production of Swithland Slate, Triassic sandstone, Lias limestone, Marlstone and Frodingham 'ironstones', Spilsby and Chalk building stone from quarries in the area - posing a significant problem for building conservation.

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Graham Lott
British Geological Survey
Nottingham NG12 5GG

LANDMARK OF GEOLOGY IN THE EAST MIDLANDS

The explosion crater at Fauld

While in no way a natural feature, the huge crater above the Fauld gypsum mine, 8 km northwest of Burton upon Trent, is one of the more bizarre components of the East Midlands landscape. It originated in one of the world's largest explosions of wartime munitions, which were being stored in the old mine. The site has changed little since then, and still warrants a visit; there is nothing else like it in Britain.

Gypsum, alabaster and anhydrite

The Tutbury gypsum is the lower of the two major gypsum horizons within the Mercia Mudstone that have been exploited in the Trent Valley region. It lies about 35 m below the Newark gypsum, and 75 m below the Rhaetic Blue Anchor Formation, the marker horizon by which the two gypsums are always traced within the monotonous sequence of red mudstones. Both beds consist of anhydrite ($CaSO_4$, anhydrous calcium sulphate) at depth.

The original gypsum ($Ca_2SO_4.2H_2O$) was deposited by incomplete evaporation of shallow saline waters in bays temporarily cut off from the sea along the desert shorelines of Triassic Britain. Conversion of the gypsum to anhydrite occurs when the increased pressures and temperatures of burial cause dehydration during the lithification process, generally at depths of around 400 m. Re-conversion, from anhydrite back to gypsum, requires only the addition of water within the deep weathering process, and generally starts when denudation lowers the surface to within about 100 m of the mineral. Both these depth figures vary with local conditions of geothermal gradient, groundwater availability and geochemistry, and it is considered that alabaster, instead of normal gypsum, was produced by rapid, cold hydration at shallow depths in a periglacial environment (Mossop and Shearman, 1973).

Today the anhydrite survives at depth, but the outcrop along the southern slope of the Dove valley, west of Tutbury (Fig. 1), is of gypsum. This forms a variable and discontinuous bed of mineral lenses that reach up to 6 m thick. Though much of the gypsum is soft, featureless and almost chalky in structure, some of it is of the stronger, crystalline, translucent variety known as alabaster (Firman, 1984). This is highly valued as an attractive and easily carved ornamental stone. The Fauld material can provide very large blocks and is notably pure and clean, with less of the red streaking that

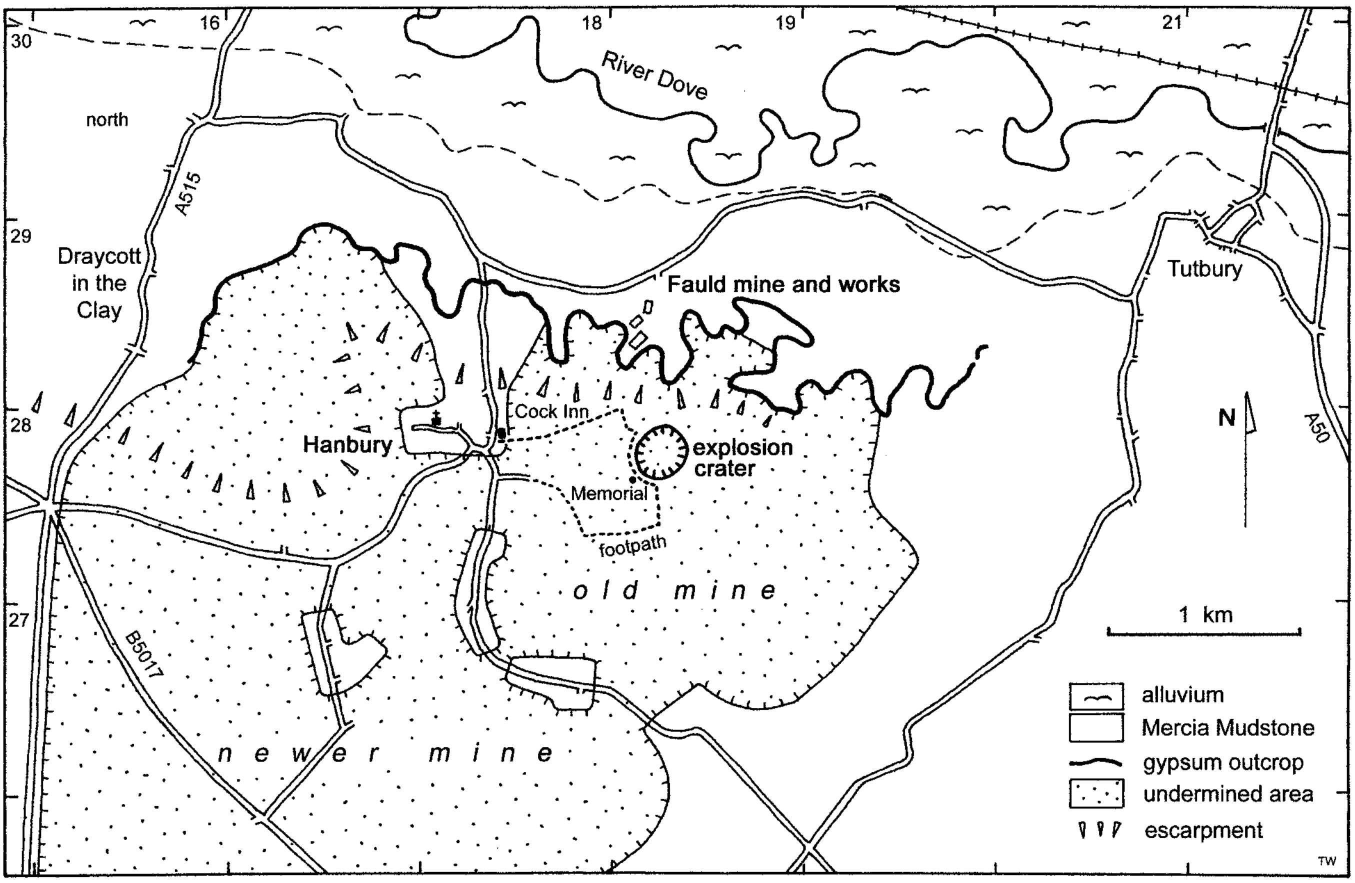

Figure 1. The area around Fauld and Hanbury.

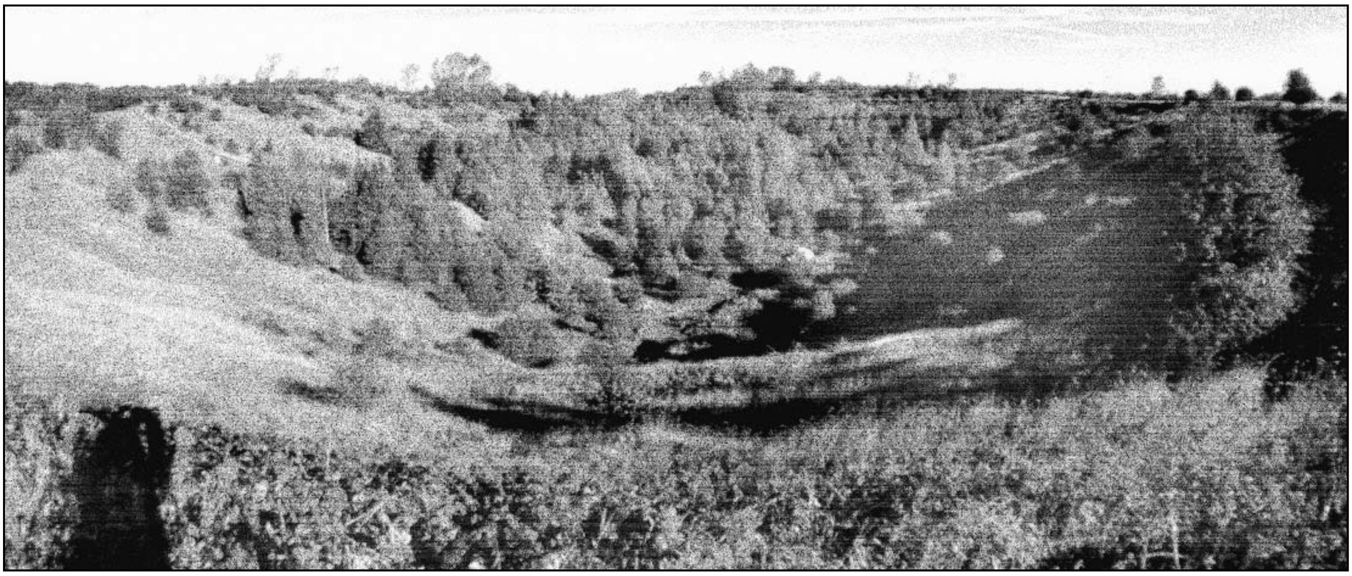

Figure 2. The explosion crater seen from its southern rim.

characterises the locally well-known alabaster from Chellaston. At Fauld, the best alabaster was found in lenses 5-12 m across, randomly distributed within the chalky gypsum.

The gypsum dips very gently to the south, and passes under the rise of a very gentle escarpment, so that its mudstone cover is up to 90 m thick a few kilometres south of the outcrop. The hills also have a thin veneer of glacial till. As the cover increases, the gypsum progressively gives way to its ancestral anhydrite. There is no clear demarcation, but an intermediate zone has a remnant core of anhydrite with gypsum at both base and top in contact with the mudstone. Joint lines also have vertical sheets of gypsum through the anhydrite, and neatly demonstrate the gradual conversion where water can reach the mineral.

Mines and mining

Alabaster was used as long ago as 1080 to build the archway over the western door of Tutbury church. The early sources were small open quarries and short drift mines along the outcrop between Tutbury and Draycott-in-the-Clay, but these are no longer recognisable. The contorted outcrop of the gypsum (Fig. 1) winds round the old quarries, with the modern and disused mine entrances at their southern ends. Further east and west the mineral bed is too thin for economic working. As time went by the mines had to extend further into the hill, and were amalgamated into fewer, larger operations. The Fauld mine dates from before 1800, when it was one of three almost horizontal drift mines into the hillside at the back of the old quarries.

All the mines are pillar-and-stall operations, whereby about 25% of the mineral was left in place to support the roof and ground above. The early workings were all for ornamental stone, and have no regular pattern, as the galleries (or stalls) followed the best quality of alabaster. The miners used blasting to excavate their headings, until they found a lens of good alabaster. Then all blasting stopped, and the stone was cut out by hand (Trafford Wynne, 1907). The roof was undercut as a “topping” slice a metre high was dug out of the poor quality upper stone. Working in this, the miners advanced until they were about 1.5 m in from the face, and then dug a gutter down to the base of the bed. They also dug out side slots. Normally the bed was about 2 m thick, and would be split free at the floor and mid-height, by hammering steel feathers and wedges into horizontal auger-drilled holes. Blocks 1 m thick, 1.5 m wide and up to 6 m long were thereby extracted intact, and hand-sawn to size, or to cut out poor stone, before being carted to daylight.

Plaster was produced by roasting gypsum and inferior alabaster, and its production overtook that of alabaster before 1900. The mines all became one and were modernised by British Gypsum, as they were extended to the southwest in a regular square grid of excavated stalls each 6 m wide between square pillars 6 m across. Production was gypsum for a plaster factory at the mine entrance, together with increasing amounts of anhydrite, which is used in cement. Small amounts of alabaster were extracted almost on demand from remaining ground in the old mine, until resources were exhausted in the early 1990s. One of the larger blocks produced in the later years was carved into a bath as a wedding present for Princess Margaret in 1960.

Today, Fauld is Britain's leading source of anhydrite, and produces no gypsum at all. The workings extend more than 6 km to the south (well off the map in figure 1), in a belt 2-4 km wide. At depths of 60-90 m the mineral is pure anhydrite. The depth also aids mine stability, as the totally unweathered roof mudstone is a strong material. Only at shallow depths, in workings many years ago, were problems occasionally encountered - with natural dissolution cavities in the gypsum and softening of roof mudstone at <15 m below rockhead. A few sinkholes developed in fields near Hanbury where weathered mudstone was met in the mine roof beneath a previously unknown gravel-filled buried valley. Except for these, subsidence has not been a big problem at Fauld. As an extra precaution, pillars of in situ gypsum have been left under Hanbury village and beneath some clusters of houses just to the south (Fig. 1). The Cock Inn at Hanbury was underpinned in 1981, but the soft weathered mudstone had probably caused as much movement as had any mining.

The explosion

In 1937 part of the old alabaster mine workings was taken over by the RAF for use as a munitions store. Up to 40,000 tonnes of bombs and explosives were stored there, all well away from the contemporary mine roadways.

On the morning of 27 November 1944, an armourer found a damaged exploder on a 450 kg bomb that was within a pile of similar bombs. It appears that he tried to remove the exploder, but used the wrong equipment (Major, 1999). At about 11am, it exploded, setting off its bomb, then the whole pile of bombs, then about 3500 tonnes of high explosive bombs stored in the immediate area of the mine.

The explosion was the world's largest accidental blast (though fortunately without the enormous death toll of the munitions ship explosion in Halifax, Canada, in 1917). It was seen or felt 60 km away, was heard in London, and was recorded on seismographs all across Europe. Well over a million tonnes of rock and soil were blasted into the sky, leaving a crater 250 m across. The bomb store in the mine had been about 35 m below the surface, and the blast hole would have reached somewhat deeper before the sides slumped in, but claims that the crater was 75 m or even 120 m deep appear to be exaggerated.

Upper Castle Hayes Farm was directly above the explosion; it completely disappeared, along with the six people in it at the time. Flying rocks damaged the church, the hall, the inn and many houses in Hanbury village. Some rock debris landed 10 km away. The dam of a small reservoir just north of the crater failed; a flood wave mixed with 50,000 tonnes of blast debris destroyed the plaster factory at the working mine entrance, killing 33 workers within. In total, 80 people died in the explosion and its aftermath.

Rocks and mud were strewn across the countryside, and the clean-up was a massive task. The Cock Inn and the Hanbury village hall were rebuilt. One section of the mine no longer existed, and adjacent areas had partially collapsed. It took a year of delicate work to remove the thousands of tonnes of ordnance that were reachable, but it is estimated that 3000 tonnes of unexploded bombs remain within the collapsed mine.

The crater today

A circular footpath has been created to make the crater rim very accessible (Fig. 1) - though wellington boots are advised for visits in the winter and wetter months. Cars may be parked at the Cock Inn, in Hanbury, where the path starts beside a notice board. It heads east across open fields and beside woodland, and then loops round the southeast rim of the crater (which centres on NGR SK183278). Large *Keep Out* signs may be appropriate in view of the unexploded bombs that must lie within. The crater is still just over 250 m across, and is about 30 m deep (Fig. 2). Its floor is a chaos of broken ground, partly obscured by trees that are now mature; blocks of white gypsum 3 m across are visible from the rim. Rotational landslides in the mudstone have modified the original blast-excavated profile, so that the slopes are now gentle and covered with plants and shrubs; they appear to have reached stability. The overall profile resembles that of old meteorite impact craters or some volcanic craters, and its sharp rim distinguishes it from typical collapse dolines in limestone.

Standing beside the rim path, a memorial to those who died in the explosion was donated in 1990 by the munitions depot at Novara in Italy, that is a sister to the RAF depots at Stafford and Fauld. It is a very fine block of white biotite granite, probably from a quarry in Sardinia.

The return path loops southward back to Hanbury, passing a small concrete blockhouse over an air-shaft into the mine. Any fields that have been recently ploughed reveal numerous small blocks of white gypsum, all of which is blast debris that originated over 30 m below ground. Even larger gypsum blocks lie beside the path, left where the farmer has cleared them from his rock-strewn fields.

Perhaps these blocks give a greater feel for the scale of the explosion, because the big hole itself is almost beyond comprehension in terms of a single blast. Even though it is man-made, the Fauld crater is now a permanent feature of our landscape.

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Tony Waltham
Nottingham Trent University

REPORT

Trent valley geology and flooding

In November 2000, major flooding affected the whole of the Trent valley, as well as its larger tributaries such as the rivers Soar, Derwent and Dove. It was the type of flood estimated to occur about once every 50 years (the 'return period'), although it was of slightly lesser magnitude than that of 1947 (source: the Environment Agency). The media gave much prominence to the consequences of this event, emphasising the severity of the damage caused where flood protection was inadequate or non-existent. Housing and farmland were inundated, and important communication routes (Fig. 1), which should have been defended against flooding, were disrupted for days afterwards. The floods occurred as the Midlands region was experiencing its wettest autumn on record, receiving 214% of the normal October rainfall (source: The Meteorological Office), and this after the ground was saturated following an abnormally wet September. But geology also played a role in determining the extent of the flooding.

In the catchment areas much of the terrain consists of mud-rich rocks of Carboniferous, Triassic and Jurassic age, covered by expanses of Quaternary till (boulder clay). These impermeable clay substrates have minimal capacity for retaining or absorbing the water, and in combination with an efficient field and urban drainage network this contributed to the extremely rapid rates of runoff to the valley floor.

On the floodplain the permeable Quaternary alluvial deposits, that normally act as 'sponges' during elevated seasonal rainfalls, became saturated. With the water table at or near the surface, and the main river channel filled to capacity and overflowing its banks, the entire floodplain was now fulfilling its natural function of accommodating excess runoff and widespread submergence was inevitable. By November 9th, when the flood-peak was at Newark, the whole of the Trent floodplain had been converted into an extremely long ribbon lake.

It is an oversimplification to say that every part of the Trent floodplain was devastated. Man-made defences, such as embankments, embanked canals and raised urban sites, saved many parts from inundation although probably contributing to constriction and ponding elsewhere. Parts of the valley also remained dry due to protection afforded by the natural topography inherent in the floodplain. This topography was determined by the complex geological and geomorphological history experienced by the Trent drainage system (Posnansky, 1960; Brandon and Sumbler, 1988) since its inception following the retreat of the Anglian ice-sheet about 425,000 years ago.

A good illustration of the way that geology influences floodplain topography, and hence determines flooding limits, is the Trent valley around Gunthorpe and Caythorpe, about 10 km due east of Nottingham. In the photograph of this area (Fig. 1), the dry land closely corresponds to outcrops (Fig. 2) of sand and gravel belonging to the Holme Pierrepont Terrace of Charsley et al. (1990). These deposits were originally part of the active Trent floodplain as it was about 26,000 years ago (Brandon, 1996), but since then the East Midlands region has experienced gradual uplift. As a result the Trent channel cut down into its earlier floodplain, dissecting it into remnants that in the case of the Holme Pierrepont Terrace now stand up to 2.5 m above the alluvium of the modern floodplain (Howard et al., in prep.). Geologists working at times of normal river flow can map out the modern floodplain alluvium boundaries (Fig. 2) by observing the commonly subtle feature that marks the slope-change surrounding the older and more elevated river terrace deposits. On the rare occasions when the whole of the modern alluvial tract is under water, a rather different perspective is presented, and it is the actual 'water line' of the maximum flood limit that forms an easily observable division between the low and the relatively higher parts of the floodplain (Fig. 1).

Can geological maps make a contribution to flood-risk assessment?

This question can be addressed by showing just one of the many examples of places where the mapped boundary of the modern alluvium (Fig. 2) corresponded closely to the maximum extent of the November floods (Fig. 1). Caution must be exercised, however, because man-made barriers, such as large housing estates or embankments, either existing or planned for the future, can cause the waters upstream to pond and expand beyond the natural floodplain limits represented by the alluvium boundary. Furthermore, the modern alluvium boundary is a subtle, feather-edge that represents only the preserved deposits of maximum flood events – the floodwaters that laid down the alluvium could have travelled further than the actual deposits left behind. For this reason historical accounts of past flood limits, and predictions as to the effect of future infrastructure development on flooding, must also be considered.

Geological maps nevertheless explain the reasons behind topographic variation on floodplains, so providing essential earth-science data that underpins historical and topographically-based flood-risk assessments of the type issued by the Environment Agency. Geological maps are also versatile; for example, there are digital versions that can be combined with DTM's (Digital Terrain Models of topography), or air photographs, to produce on-screen 3-dimensional manipulations of floodplains and their catchment areas. It is the integration of such information, including geology, which enables a holistic approach to be made to the problem of constructing models for accurately predicting the effects of future floods.

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John N Carney
British Geological Survey

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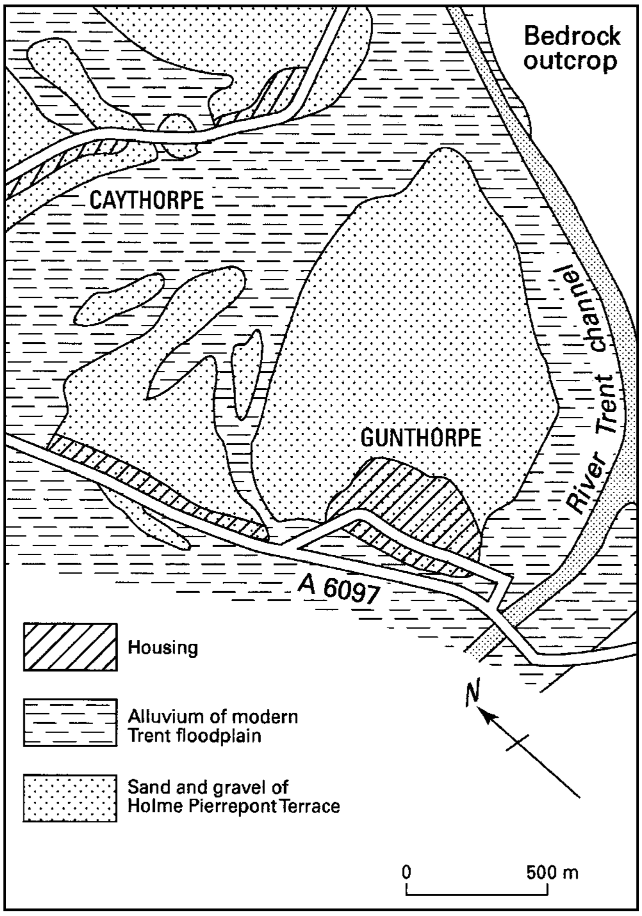


Figure 2. Geological map of part of the Trent floodplain, including the area photographed in Figure 1 (after BGS, 1:50,000 Sheet 126, Nottingham, 1996)

Figure 1. Aerial view of the Trent valley between Gunthorpe and Caythorpe (SK680450) looking downstream, towards the northeast, at midday on November 9th, 2000. (Photo: A. Forster, BGS).

REPORT

Sand towers on a raised beach near El Medano, Tenerife

The Canary Islands lie 200-300 km off the northwest African coast and rise from the Atlantic Ocean floor where it is 4000 m deep. They are mainly basaltic shield volcanoes formed over an intraplate mantle plume or ‘hot spot’. The oldest island, Fuerteventura dates to 22 Ma, and Holocene eruptions have occurred on all islands except La Gomera. Teide is a massive, complex volcano rising 3718 m above sea level on Tenerife. The later vulcanism is substantially felsic with trachyte and phonolite magmas.

While on a tour of the Canary Islands volcanoes, led by Dr Simon Day for the Natural History Museum, we stayed at El Medano, a small resort on the south coast of Tenerife, too close to the new airport to now be popular. A headland at the south end of the bay is crowned by the rather elegant scoria cone of Roja, and was an excellent destination for an evening walk. Our route took us round the bay and up onto a raised beach. In a flat sandy area with sparse vegetation, we came across some unusual features – reminiscent of the Clanger’s homes on 1970s children's television!

There were at least fifty of these structures in a single group, each protruding from loose sand, and up to a metre apart. The basic shape was a small circular tower, 100-200 mm in diameter, with walls of cemented sand 20-40 mm thick around a central hole. Some were amalgamated into oval structures with a larger central hole, while others had a number of branching tubes leading to circular holes on the outside. They stood about 200 mm high above the general ground level. They were firmly anchored to underlying rock, which appeared to be a pale, fine-grained, Holocene ignimbrite, similar to others exposed along the coast.

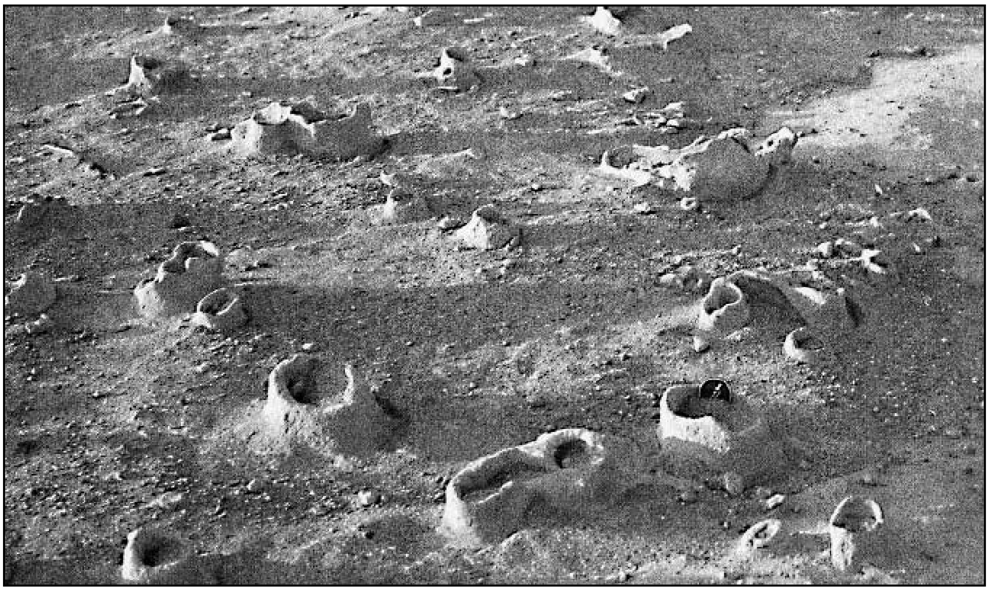
The cemented sand was a little greyer than the pale loose sand that surrounded the towers. Seen through a hand lens, the sand grains were angular, sorted to a fairly uniform size, with some grain alignment in the lower part. Black, beige and brown mineral crystals were mixed in with cream shell fragments. Hundreds of serpulid worm tubes, each > 1 mm in diameter, were seen on the inside and outside of some towers, mainly on the northern faces, but broken surfaces showed that they were superficial and were not inside the sand.

We consider that these structures were formed within the beach sand, during the Holocene, when hot aqueous fluids were rising through the ground during an eruptive episode. Hydrothermal fluids tend to rise through bedrock at fissure intersections, discharging as point sources into the sediment cover. As the fluids rose though the sand, they created pipes by mineralising and cementing the sand immediately around them. Subsequently the surrounding loose sand was removed by wave or wind action. The small worm tubes on both inner and outer surfaces indicate subsequent immersion in seawater, and further erosion may have taken place following uplift of the beach. We will never know the height of the original structures. Pipe feeders were not observed in the rock below the sand towers, but there was no opportunity for excavation and investigation.

The site is threatened by aggregate quarrying, but the towers are strong enough to last for years, and may remain accessible for examination.

Comparisons may be made with pipe structures elsewhere. The Pinnacles near Crater Lake, Oregon, some towers on the ignimbrite now flooring the Valley of 10,000 Smokes, Alaska, and the tufa columns at Mono Lake, California, are all on a much grander scale. They were all formed by rising mineralised water, but their processes varied in detail. The Tenerife features are perhaps most akin to the Alaskan towers. Write to the editor if you have any other ideas.

Philip and Judy Small



The sand towers of El Medano. The lens cap in the tower on the right is 50 mm across

REPORT

Periglacial features and ice wedge in Thornhaugh Quarry

In October 2000, Alan Dawn led a most interesting Society field excursion to three quarries beside the A47 road between Wansford and Duddington. These exposed the Lincolnshire Limestone Formation and the underlying Grantham Formation ("Lower Estuarine Series") of the Middle Jurassic, but as an added bonus, a variety of periglacial structures were well displayed at Thornhaugh Quarry. These structures most likely date from the Devensian (Oxygen Isotope Stage 2), when this part of England, although not covered by ice, suffered a periglacial climate for a prolonged period. However they could date from any cold period since the area was last glaciated in the Anglian stage (OIS 10).

Thornhaugh Quarry exposes the Lincolnshire Limestone, and the features of a periglacial active layer could be recognised in an abandoned face (Fig. 1). The limestone at the base of the face is not heavily weathered: it retains its massive nature, and although the surfaces have weathered brown, mainly due to insoluble residue washing down cracks, fallen blocks from the lower part of the massive unit retain blue-grey unweathered hearts. This massive limestone is overlain by weathered, thinly bedded limestone, which still retains its original bedding, and then by a bed of jumbled limestone blocks in a matrix of comminuted limestone and sand, up to about 1.5m thick. The base of this jumbled bed is channelled into the thinly bedded limestone below, in places coming to rest on the massive bed.

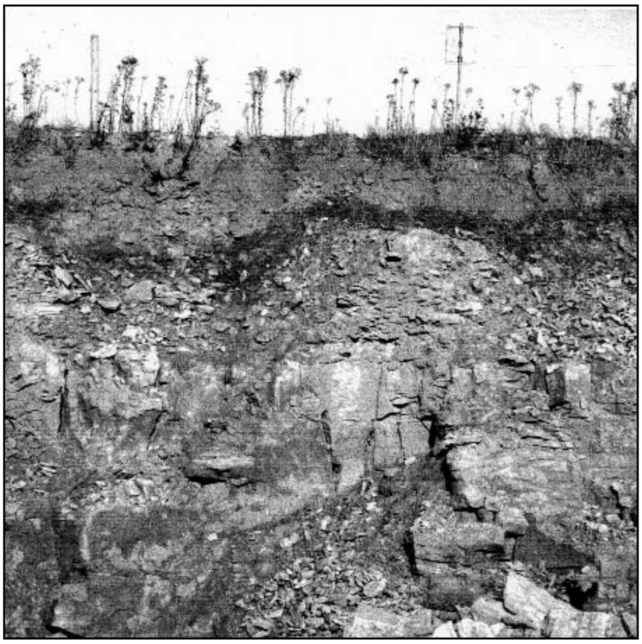


Figure 1. Cryoturbated top of the Lincolnshire Limestone in Thornhaugh Quarry.

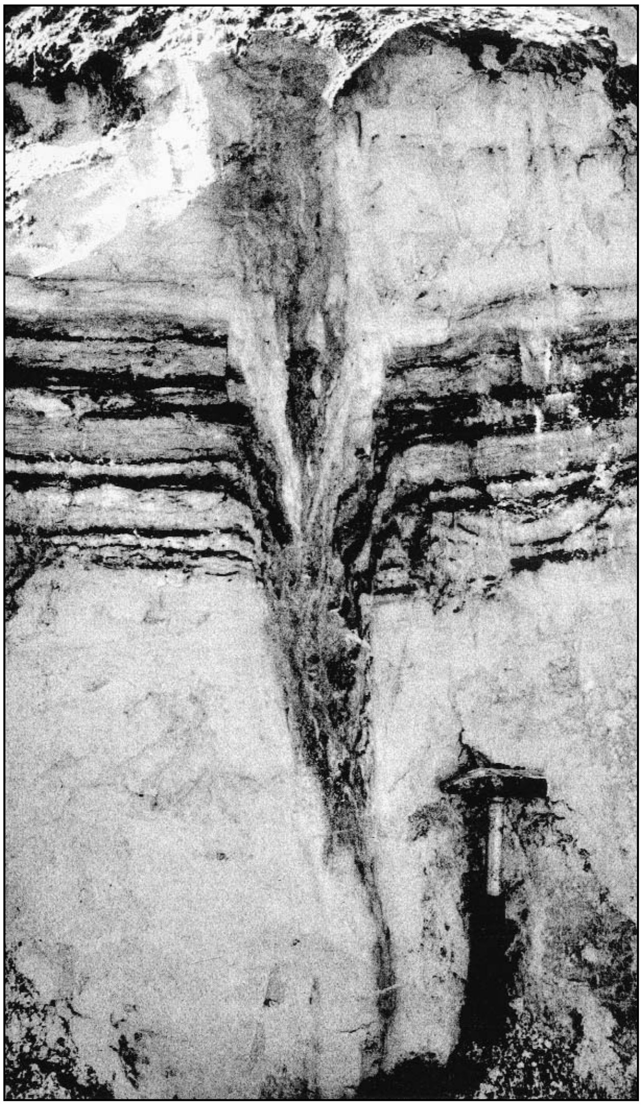


Figure 2. The ice-wedge cast in the sands of the Grantham Formation in Thornhaugh Quarry.

The jumbled bed is interpreted as the periglacial active layer. This is the layer in which groundwater freezes each winter and thaws each summer, on top of the permafrost layer which is beyond the influence of summer warming from above. These two layers are characteristic of periglacial conditions. The underlying bedded limestone remained permanently frozen, while the growth of ground ice within the upper part of the limestone split the massive rock into much thinner beds. The permafrost restricted downward drainage, and maintained a high water table in the overlying active layer during the period of summer melt. This encouraged mass movement, gelifluction, of the active layer, even on very shallow slopes. The surface layer is described as cryoturbated, because it owes its structure to the disturbance by cold processes.

Several apparent ice-wedge casts were observed within the unlithified sands of the Grantham Formation in the floor of the quarry, and the best exposed of these is shown in Figure 2. This structure was preserved over a height of about 1.3m, but it was estimated by the leader that about 6 m of the overlying Lincolnshire Limestone would have been quarried away, so the wedge must have been at least 7 m deep originally. The width of the infilled wedge tapers downwards from about 15 cm to zero, and it is filled with vertically bedded coarse pebbly sand which was clearly not derived from the immediately adjacent Grantham Formation. The bedding in the latter is clearly delineated by black, carbonaceous horizons, which demonstrate both down-folding and small-scale normal faulting into the structure.

There has been controversy recently about the origin of apparent ice-wedges described from the British Quaternary, with Worsley (1996) arguing that many water-escape structures have been misinterpreted as ice-wedge casts, leading directly to misinterpretation of climatic history. However, Fish et al. (1998) report a feature at Trimingham, Norfolk which they interpret as a composite-wedge formed in a periglacial climate, reflecting fissuring due to thermal contraction and infilling with wind-blown sand and locally-derived surface material. The combination of both wind-blown and mass-moved material means that the fissure was both open (so that sand could be blown in) and filled with ground ice (so that material could collapse in when the ice melted). Thus a composite wedge indicates both aridity and moisture in a permafrost environment.

The structure at Thornhaugh closely resembles the one in Norfolk, with similar normal faulting and vertically bedded sand infill, although at Thornhaugh it was unclear if the infilling sand was blown in from a distance or derived from the overlying weathered Lincolnshire Limestone. There was no evidence of compressive upturning or thrusting associated with the growth of ground ice. The sequence of events started when a ground contraction crack formed by thermal contraction associated with the ground freezing at the onset of periglacial conditions. This crack then became infilled with allochthonous sand, and some snow, most likely wind-blown from the surrounding area. Finally the ice and snow thawed with climatic warming, causing normal faulting at the edges of the wedge as the host sediment settled.

Jim Rose is thanked for helpful comments during the writing of this note, which is published with the permission of the Director, British Geological Survey.

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Richard Hamblin
British Geological Survey

REPORT

A very large Bradgatia fossil

The Golf Club Quarry, in Charnwood Forest, Leicestershire, contains a very large specimen of *Bradgatia* aff. *linfordensis* that has been described by the writer (Boynton, 1999). The specimen was then noted to be over a metre long, and preserved as a faint trace of fronds and discs stretching over a large area on one of the uppermost bedding planes in the quarry.

On closer scrutiy of enhanced photographs, more detail has now come to light. The fossil trace is much longer than originally thought, and consists of two prominent ovoid two-ringed discs. From one of these a rhachis emerges on two opposing sides and one of these shows bifurcation into branches. This prominent disc and other smaller ones all occur scattered through a mass of faint anastomosing fronds, together with a number of small knob-like structures. The idea that this very large organism was buoyed by the discs and floated in the sea like a massive seaweed colony today is still retained.

The name *Bradgatia* aff. *linfordensis* is given as the specimen could be a variant of *Bradgatia linfordensis*, which was first described from the Memorial Crags in Bradgate Park (Boynton and Ford, 1995).

The Golf Club Quarry specimen does show some differences, in that it contains a number of small discs associated with the mass of fronds. These are not found in the holotype at Memorial Crags. Due to the faintness of the trace of this very large frondose specimen, it can only be seen under exceptional lighting conditions that may occur in mid-summer, and by studying enhanced photographs taken of the washed bedding plane when it has been left slightly damp. This is the first record of such a large frondose specimen, over 2 metres long and up to 500 mm wide. Further similar fossils may still await discovery, but their faintness and the necessity for optimum lighting conditions makes them very elusive to detailed description.

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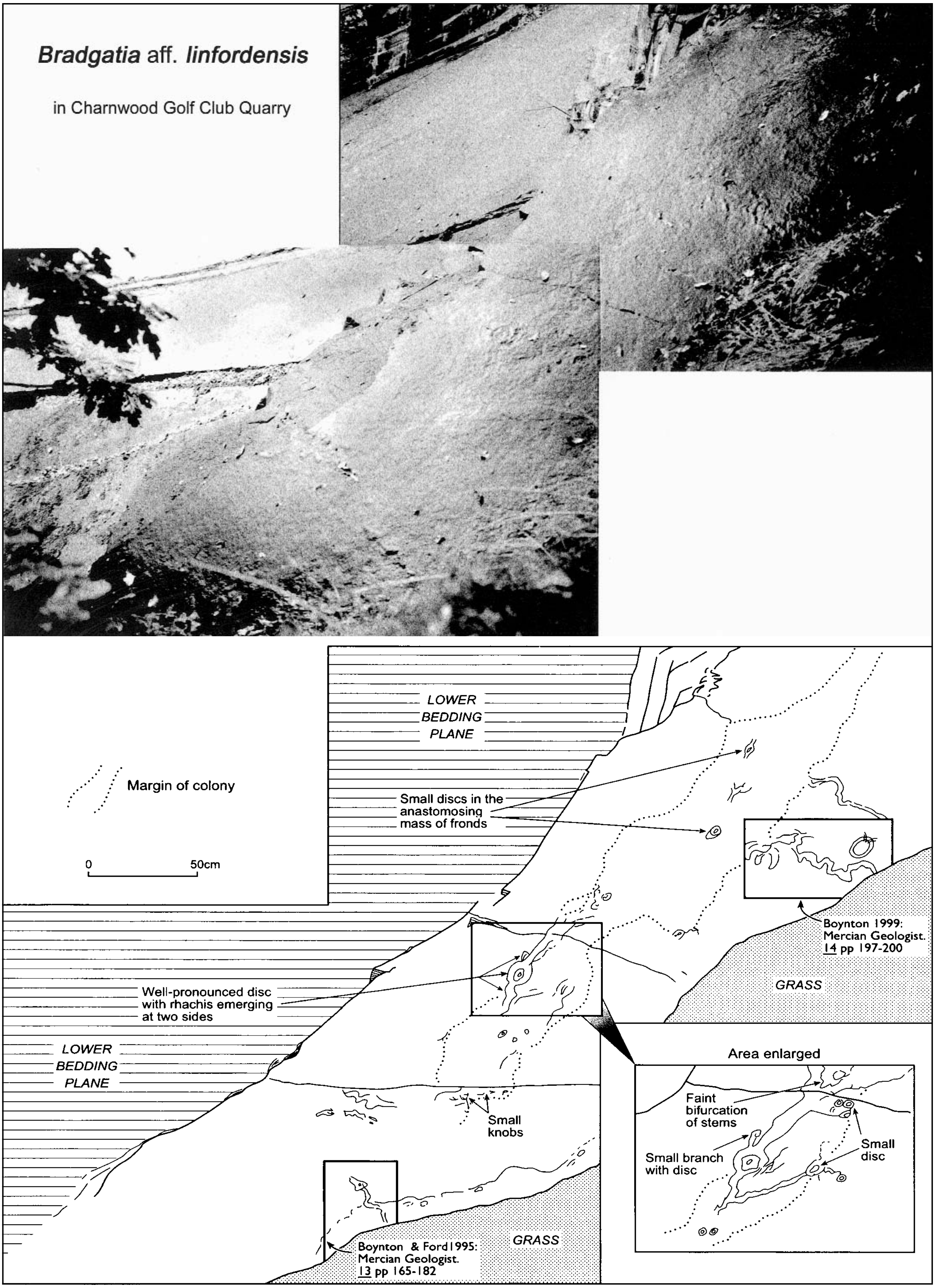
Helen Boynton



Bradgatia aff. *linfordensis*

in Charnwood Golf Club Quarry

REPORT

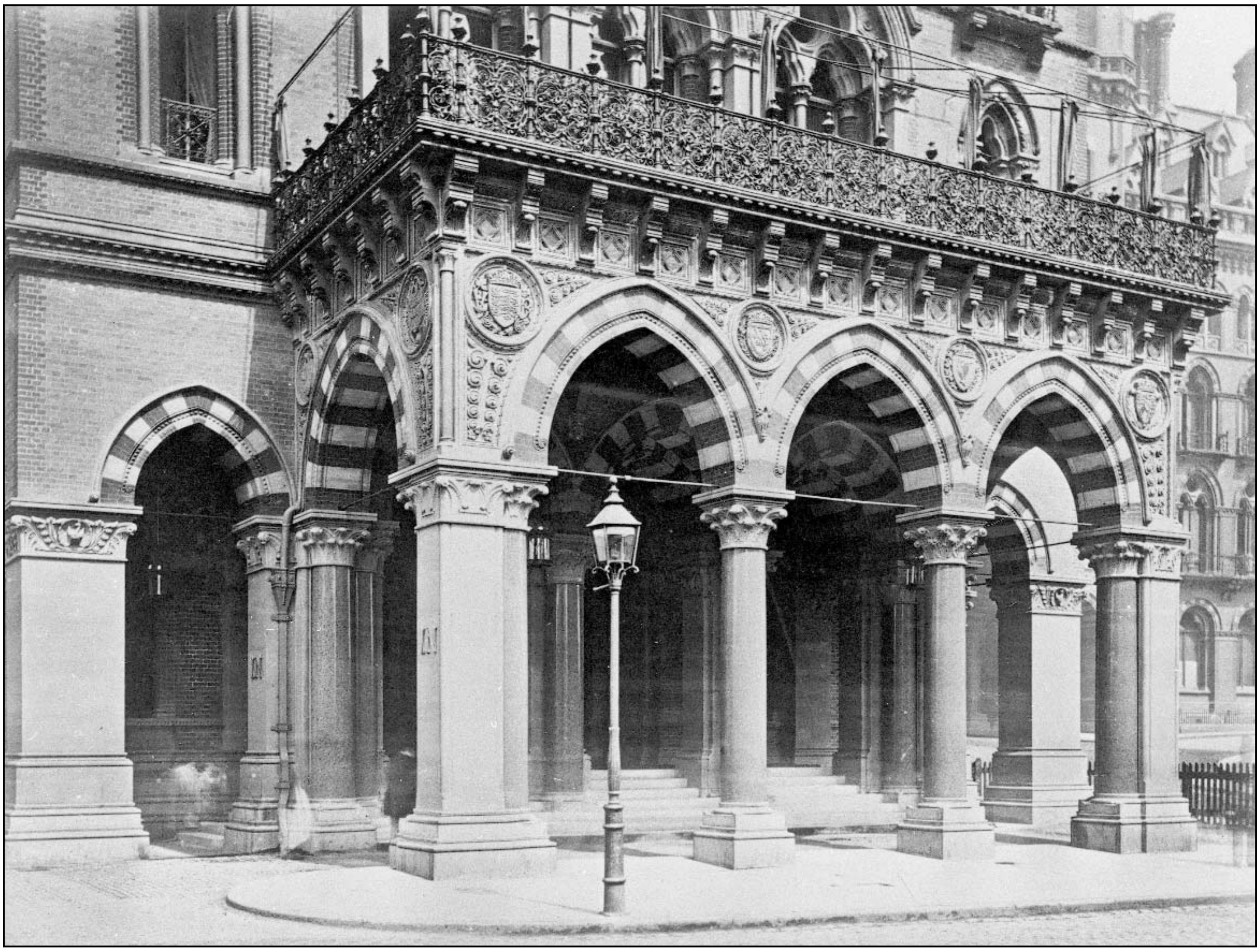
St Pancras celebrates the Midlands

The Midland was the last of the main railway companies to reach London, but it did so with a flourish. St Pancras Station has style. Not only did the Midland have the Butterley Iron Company produce the splendid giant roof that arches over the tracks and platforms, but it also built its catchment geology into the drama of the hotel across the station frontage. The Midland directors allowed their chosen architect, Gilbert G. Scott, to indulge his passion for the elaborate Gothic style.

The architectural magazine of the day, The Builder, hailed St Pancras as “a powerful piece of showmanship, and that was just what the company required. It made Euston appear the old fashioned muddle that it was, and King’s Cross a very ordinary piece of austere engineers' building. The Midland Board were business men, making their choice on the broadest commercial grounds”.

What were those commercial grounds? Anyone travelling from Nottingham to London and coming out onto the terrace above Euston Road should still feel at home. There are columns and capitals carved in buff and pale pink Sherwood Sandstone from Mansfield. There are capitals carved freely in Ketton and Ancaster Stones. Some kerbs are grey-green Swithland Slate from Charnwood. The granites are not from the Midlands, but like the other stones in the visible building fabric, they were proclaiming “If you like it, we can supply it over our network of lines from the quarries to the Somers Town goods yard alongside this station”. It was a blatant advertisement, promoting their goods services at attractive rates.

The use of many different colours and textures in the materials was an integral part of Scott's design, just as it had been in the Albert Memorial ten years earlier. He loved to feature columns of polished granite. The grandest of these flank the station entrances with Shap Granite, so easily recognised by its large feldspar crystals. Smaller columns are of Peterhead Granite, pale pink, lighter than the Shap and non-porphyritic.



The ornate main entrance to the St Pancras Hotel, now disused on Euston Road. The round columns are single blocks of polished Shap Granite, standing on unpolished plinths of the same stone, while the square columns at the corners are stacked blocks of Sherwood Sandstone from Mansfield. Capitals of the same sandstone support arches of alternating dark bricks and light Ketton limestone.

The Midland's claim to Peterhead relied on working agreements with Scottish companies including the Caledonian and the North British, and Shap lay well inside London and North Western territory, but some of the supply lines were engineered by the Midland itself. The company's role in the discovery and exploitation of the Northampton Sand Ironstone is well known. Their venture eastward from the main line to Stamford allowed them to tap the stone traffic from sources in the Welland Valley, thanks to the diversion of the Great Northern's line by the Burghley Estate.

Alongside the block of dimension stone, millions of red bricks all came from within the Midlands network. These were the special contribution of Stapleford, the product of the innovative Mr Gripper, an Essex farmer who moved to the Midlands to open up a brickworks well ahead of its times. Using a mix of Pleistocene clay and weathered Mercia Mudstone (then known as Keuper Marl), he produced at low cost a very hard surfaced red brick by using an adaptation of the Hoffman kiln from Germany. In this process, hot gases from a fired kiln chamber preheat the next chamber containing "green" bricks. This saves fuel, and it brought Gripper's rates down to 50 shillings per thousand for best "fronters" and 37 shillings per thousand for "commons" - very competitive prices indeed for the late 1860s.

Today, St Pancras is still the London gateway to the East Midlands, and its future should be assured as the permanent terminus for Eurostar trains to and from the continent. No grander entrance or departure point could be created for visitors to this country, more so if they happen to be geologists.

Eric Robinson

Dragons carved on the capitals of Mansfield sandstone.

THESIS ABSTRACT

Sedimentological, palaeogeographical and stratigraphical aspects of the Middle Pleistocene geology of the Peterborough area, eastern England

Harry E. Langford
Geography Dept, Anglia Polytechnic University
sagemO3644@talk21.com

A sedimentological study of Middle Pleistocene deposits in the Peterborough area has been undertaken in order to determine their genesis, and to develop palaeogeographical and stratigraphical models. The deposits were divided into two categories on the basis of published descriptions - (1) Anglian chalk-rich diamictons, which locally may overlie deep sequences of lacustrine muds, sands, diamictic muds and matrix-supported diamictons, and (2) post-Anglian sand and gravel bodies forming fluvial terrace aggradations.

The Anglian sequences are interpreted to have been deposited subaqueously in a lake that at times may have covered the present-day area of the Fen Basin. Contrary to prevailing models of Anglian glaciation, there is no unequivocal evidence for glacial overriding of the Peterborough area from the northeast, and the timing and origin of the breaching of the Chalk escarpment at The Wash remains equivocal. Triassic-rich phases suggest that the easterly limit of ice advancing from a westerly direction during this stage was closer to Peterborough than prevailing models suggest, although it appears to have remained to the west of Peterborough.

Sequences in post-Anglian deposits suggest major Middle Pleistocene reorganization of fluvial networks in the Fen Basin. Southerly directed meltwater flow from a post-Anglian, but pre-Devensian, ice sheet to the north of the Fen Basin deposited a fluvial sequence to the north of Uffington and formed the Southorpe dry valley. Formation of an alluvial fan at the southern end of the dry valley impounded waters of the former River Nene to create a lake at Elton. The origin of some of the River Nene 3rd and 2nd terraces, and some of the incised bedrock meanders, can be explained by the presence of the lake at Elton and by flow through the Southorpe dry valley. Formation of the River Welland during this phase diverted flow from the Southorpe dry valley.

Stratigraphical interpretation of fluvial sequences at King's Dyke and Sutton Cross, based on age-estimates from the former, suggests that the major drainage reorganization occurred during Oxygen Isotope Stage 8.

PRESIDENTIAL ADDRESS

The later Crags and associated fluvial deposits of East Anglia

Summary of one part of the address to the Society on Saturday 12th February 2000, by Dr Richard Hamblin of the British Geological Survey.

I have been working in East Anglia since 1991, on a mapping project led by Brian Moorlock. There have been up to four people in the team, other members at various times being Steve Booth, Tony Morigi, Dennis Jeffery, Mike Smith and Holger Kessler. I must also mention Professor Jim Rose of Royal Holloway, University of London, and many of his students, with whom we have had a very constructive collaboration since the early nineties. Many of the analyses presented in this address are theirs. When I joined the project we were surveying the Saxmundham (191) and Lowestoft (176) 1:50,000 sheets in Suffolk, and we later moved north to survey the North Walsham (148), Mundesley (132) and Cromer (131) sheets in Norfolk (Figure 1).

The Quaternary of East Anglia falls broadly into three major divisions: the marine Crag Group, a series of pre-Anglian fluvial formations which drained into the Crag sea, and finally the glacial and post-glacial deposits which were formed from the Anglian Stage onwards. The Crag Group is divided into four formations: from the oldest these are the Coralline, Red, Norwich and Wroxham Crag formations. The Coralline Crag is Pliocene, while the others are Early Pleistocene (Table 1). They were deposited on the western margin of the North Sea basin, which was subsiding and variably deforming throughout the period. The Crags are dominantly composed of glauconitic, micaceous sands, commonly shelly, with units that are rich in gravel, and frequent interbedding of silts and clays.

Red Crag and Norwich Crag

Our work in Suffolk largely involved resurveying the Red and Norwich Crags (Hamblin, *et al.*, 1997; see therein for further references), as well as the overlying glacial deposits. In the past, many divisions of these Crags have been proposed, but as lithostratigraphical units, most have not stood the test of field mapping. However, our colleagues Steve Mathers and Jan Zalasiewicz, working in Essex and southern Suffolk, were able to distinguish in the field between the coarse, shelly sands of the Red Crag and the well-sorted, fine-grained sands of the overlying Norwich Crag. They subdivided the Red Crag into Sizewell and Thorpeness members, on borehole evidence, and the Norwich Crag into Chillesford Sand and Chillesford Clay members, both of which are mappable units (see Table 1).

The Red Crag rests unconformably upon the Coralline Crag and oversteps onto Palaeogene deposits and Upper Chalk. Our own surveys in northern Suffolk confirmed the validity of the Red and Norwich Crag formations, and revealed a further unconformity at the base of the Norwich Crag, which similarly oversteps the Red Crag to rest upon the Palaeogene deposits and Upper Chalk. This is the sub-Antian/Bramertonian unconformity shown in the cross-sections on Figure 2, which are based on borehole evidence. From a study of the contours on the bases of the two formations, and building on the work of Bristow (1983) in mid-Suffolk, we concluded (Hamblin et al., 1997) that the Red Crag was formed in a series of NE-SW marine basins, most likely controlled by contemporaneous faulting, while the Norwich Crag is represented by a thin but widespread sheet of tidal flat and coastal sediments with less evidence for tectonic effects.

Our mapping demonstrated that the Chillesford Clay outcrop does not extend very far north of Aldeburgh, but farther north, a series of interbedded clays, sands and gravels of approximately the same age (Baventian stage) occur around Easton Bavents and Covehithe (Figure 3). All these clays are very silty, with silt and sand laminae, lenticular bedding,

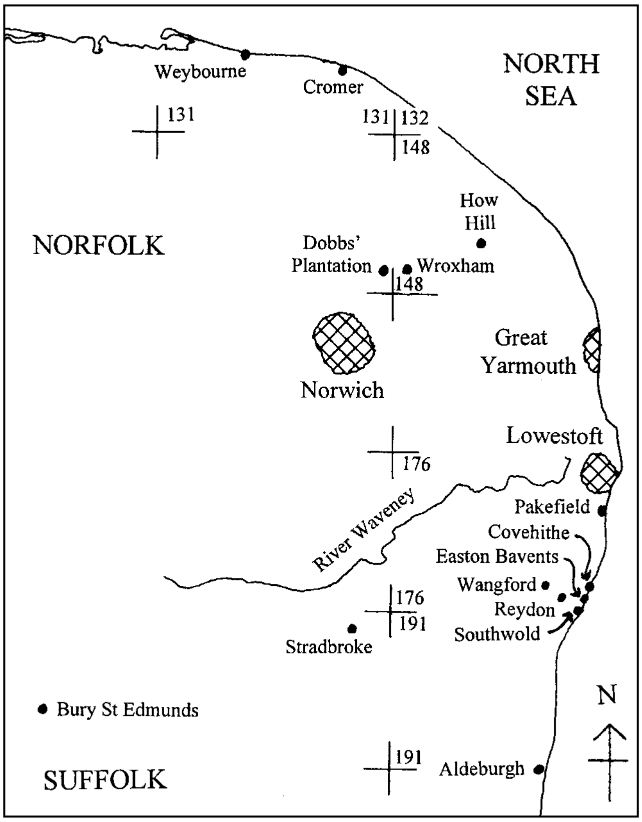


Figure 1. Locality map. All places cited in the text are shown, along with the limits of 1:50,000 map sheets 131 (Cromer), 132 (Mundesley), 148 (North Walsham), 176 (Lowestoft) and 191 (Saxmundham).

Table 1. Lithostratigraphy of the Crag Group and equivalent fluvial formations, and the English stages of the Early Pleistocene, modified after Hamblin *et al*, 1997.

Stage	Lithostratigraphy of the Crag Group		Fluvial Formations		
Cromerian	Wroxham Crag Formation		Kesgrave Formation	Bytham Formation	Cromer Forest-bed Formation
Beestonian					
Pastonian					
Pre-Pastonian					
Baventian	Norwich Crag Formation	Westleton Beds, Chillesford and Easton Bavents clays	Nettlebed Formation		
Antian/Bramertonian		Chillesford Sand			
Thurnian	Red Crag Formation				
Ludhamian		Thorpeness Member			
Pre-Ludhamian		Sizewell member			

ripple-drift cross lamination, plant remains, marine molluscs and foraminifera, and desiccation polygons; these last two elements indicate that the clays range from shallow marine to supratidal in origin. As a guide to the provenance of these clays, our colleague Jim Riding studied their derived micropalaeotology (Riding *et al.*, 1997). In the Chillesford Clay he recorded Silurian acritarchs, Westphalian spores and Jurassic miospores and dinoflagellate cysts. The Easton Bavents clays were dominated by Jurassic miospores and dinoflagellate cysts, and Carboniferous spores. This dominance of relatively ancient derived microflora demonstrated that the clays were not deposited in an open sea environment, since in such a situation, material derived from river transport would be swamped by contemporary marine forms and by Quaternary, Tertiary and Cretaceous forms derived from the bed of the North Sea. Hence, we concluded that the clays formed in tidal river estuaries or lagoons.

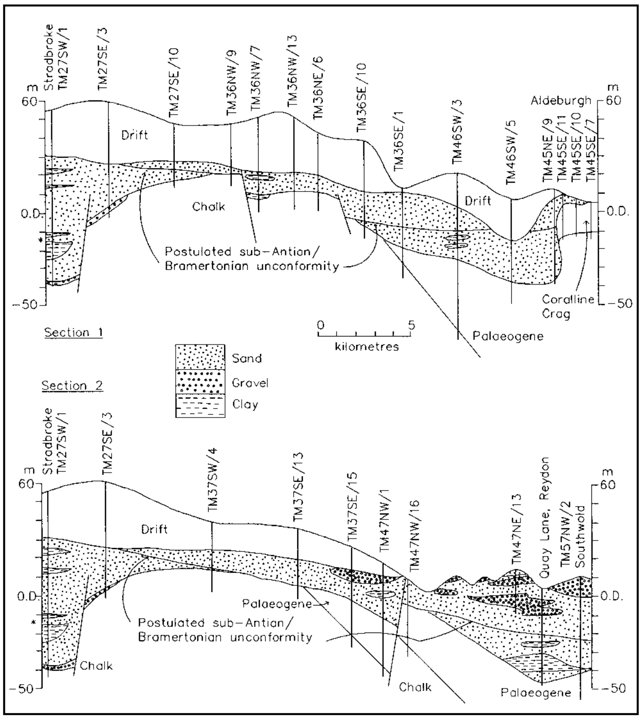


Figure 2. Generalized cross-sections through the Red and Norwich Crag formations from the Stradbroke Borehole to Aldeburgh and Southwold, after Hamblin *et al.* (1997). Vertical exaggeration x100. Boreholes are labelled with BGS registration numbers. The asterisks mark the Ludhamian : Pre-Ludhamian boundary in the Stradbroke Borehole. The base of the Antian/Bramertonian sediments has only been proved at Aldeburgh; at Reydon it has been taken at the top of proven Thurnian strata.

The contemporary rivers

At this point it is necessary to consider the rivers that drained eastwards into the Crag sea (Figure 4). The deposits of the proto-Thames are represented by the Nettlebed Formation and the Kesgrave Formation (Rose et al., 1976; see Rose *et al.* 1999 for further references). The Nettlebed Formation gravels comprise 98% flint and only 0.7% quartz and quartzite, but the later Kesgrave Formation gravels contain 20-30% quartz and quartzite, up to 3% Greensand chert and up to 1% acid volcanics. The latter demonstrate that the river flowed from Wales. The proto-Thames followed a more northward route to the sea than the present-day river, later being diverted into its present course by the advance of the Anglian ice sheet. Hence, bearing in mind the age of the derived microflora in the Chillesford Clay, it is probable that the Chillesford Clay represents the estuary (in Baventian times) of the proto-Thames, with the Silurian acritarchs being transported from the Welsh Borders and the Carboniferous and Jurassic forms from the English Midlands.

Farther north than the proto-Thames, the Bytham River (Rose, 1987, 1994; Hamblin and Moorlock, 1995) flowed from the West Midlands and southern Pennines, across the area now occupied by Fenland, crossing the Chalk outcrop at Bury St. Edmunds and then following roughly the line of the present River Waveney. The river was destroyed when the Anglian ice advance buried its catchment. The gravels of the Bytham River are rich in quartz and quartzite (20-70%) as well as flint (30-80%). Compared to the Kesgrave gravels they contain a higher proportion of quartzite than quartz, with much of the quartzite, derived from the Kidderminster Conglomerate of the English Midlands, being red and brown in colour. They also contain up to 4% of Carboniferous chert from the Pennines, and traces of Spilsby Sandstone from south Lincolnshire and north-west Norfolk, but no acid volcanics or Greensand chert. In view of the derived micropalaeotology of the Easton Bavents clay, with Jurassic and Carboniferous forms but no Silurian, we believe that the clays around Easton Bavents formed at the Bytham River estuary.

The gravels interbedded with the clays around Easton Bavents are termed Westleton Beds, and are coarse, well-sorted, clast-supported gravels formed almost wholly of high-sphericity, well-rounded to sub-angular chatter-marked flints. They contain marine molluscs and whale vertebrae, implying a marine origin, and occur in 10m-thick cross-sets, dipping towards the south-east (Mathers and Zalasiewicz, 1996; see therein for earlier references). The gravels represent a complex of regressive beach-face gravel banks, thrown up by the sea as it retreated south-eastwards. Taken in connection with the estuarine clay bodies it is probable that the clays formed in a shifting complex of muddy lagoons and quiet estuaries protected to seaward by the shoreface gravel banks: in a modern context, if the gravels represent Dungeness, the clays would represent Romney Marsh. The gravels would not be expected to yield any micropalaeontological evidence of derivation, but the non-flint clasts (up to 4% of the total) include quartzite and quartz from the Kidderminster Conglomerate of the English Midlands, "spicular" flints from the Chalk of Lincolnshire, and Rhaxella chert from the Corallian Group of North Yorkshire. This agrees with our interpretation of the clays as occupying the estuary of the Bytham River. The low proportion of non-flint clasts of the Westleton Beds compared to that of the surviving river gravels suggests that the latter formed at a later period in the development of the river than the (Baventian) Westleton Beds, after increased downcutting had led to a higher yield of pebbles from the Midlands.

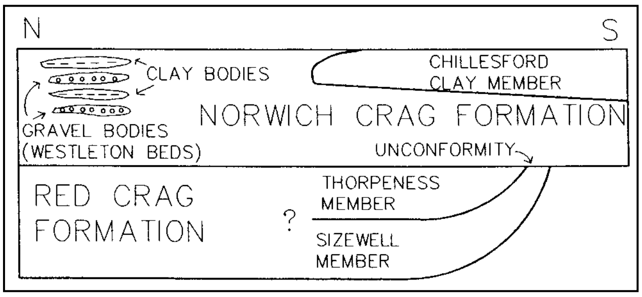


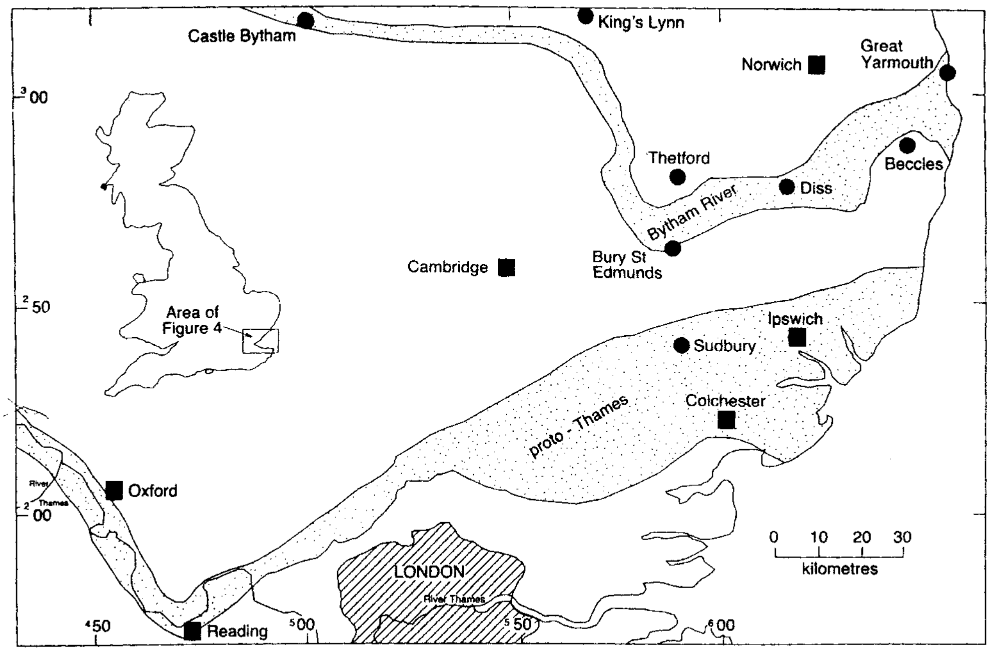
Figure 3. Diagrammatic relationships between the lithostratigraphic components of the Red and Norwich Crag formations from around Aldeburgh to around Southwold, after Hamblin et al (1997).

The stages of the Quaternary (Table 1) were derived largely from the micropalaeontological work of Richard West and Brian Funnell in the 1960s (see Hamblin *et al.* 1997 for references). Using pollen assemblages and foraminifera, they subdivided the Quaternary on climatic grounds, separating warm stages (Ludhamian, Antian/Bramertonian, Pastonian) and cold stages (Pre-Ludhamian, Thurnian, and Baventian/Pre-Pastonian). The regressions and transgressions within the Crag Group can apparently be related to these climatic changes, suggesting a relationship with glacio-eustatic changes in sea level. The Red Crag Formation ends with a regression during the cold Thurnian, while the Norwich Crag starts with a transgression during the warm Antian and ends with a regression in the cold Baventian, resulting in deposition of the estuarine clays and the beach-face Westleton Beds. Mathers and Zalasiewicz (1996) recorded deeper-water sediments overlying the Westleton Beds at Reydon, indicating a further transgression, but this will be discussed later; meanwhile, it is necessary to again consider the rivers draining into the Crag sea.

Our surveys of the Saxmundham and Lowestoft sheets, coupled with Jim Riding's work on the Chillesford and Easton Bavents clays, confirmed the paths of the proto-Thames and Bytham rivers as shown in Figure 4. However, contemporary wisdom at the time held that these rivers had only followed these routes late in their history, immediately before the Anglian transgression. At an earlier stage they were believed to have followed a more northward route still, joining together in northern Suffolk and continuing to cross the present-day coast near Cromer in North Norfolk. Our claim (Hamblin and Moorlock, 1995) that they had never flowed farther north than is shown in Figure 4 brought forth a spirited response from Rose *et al.* (1996a), including a very useful map of numerous sites in Norfolk that yielded gravels of Kesgrave or Bytham lithology.

This worried us at the time, could we have been wrong all along? We reasoned that we must be right: since we were convinced of the routes of the two rivers during the Baventian, we could see no reason why the Thames should later move to a more northward route. The answer emerged soon after from our studies in Norfolk, since by now we had started surveying the North Walsham sheet. We visited several of the sites listed by Rose et al.

Figure 4. Courses of the pre-Anglian proto-Thames and Bytham rivers, modified from Hamblin and Moorlock (1995).



(1996a), although many were no longer exposed, and arranged with Jim Rose and his students for trial pits at How Hill (Figure 1) (Rose et al. 1996b). We discovered that almost all of the gravels in question were in fact marine, rather than fluvial. This meant that they did not belong to the Kesgrave or Bytham formations, which are by definition fluvial, but are a part of the Crag Group. We established the name Wroxham Crag Formation to cover this new unit, which differed from the Norwich Crag in that its gravel fraction contained a high (>10%) non-flint component, compared to the low (<4%) non-flint component of the Norwich Crag (Westleton Beds). We reasoned that the distinctive Kesgrave and Bytham gravel fraction of the Wroxham Crag had entered the sea at the river mouths in Suffolk and had been transported north by longshore drift or coastal currents.

The How Hill trial pits yielded more interesting information on the river systems. The gravels analysed were 52-69% flint, 22-39% quartz and quartzite, and up to 7.7% Carboniferous chert, 0.6% Rhaxella chert, 2.1% Greensand chert, and 0.3% igneous. The ratio of quartzite to quartz worked out at 1.25:1, and the quartzites were dominantly white or colourless, both of which features are more typical of the Kesgrave than the Bytham gravels. This was surprising for a deposit so far north. However, the percentages of Carboniferous and *Rhaxella* chert, derived from the Pennines and North Yorkshire, was far higher than in either the Kesgraves or Bythams, and we take this to indicate a major input from a further river flowing from that direction. Input from this "Northern River", rather than a high Kesgrave input, would be the explanation for the high proportion of white and

Figure 5. Bedded sands and gravels of the Westleton Beds exposed in the cliffs at Dunwich.

colourless quartzites. It thus appears that during the Early Pleistocene, East Anglia was traversed by three major rivers flowing from west to east, the proto-Thames, the Bytham and this "Northern River", which is now named the Ancaster River (Clayton, 2000).

We believe that the fluvial deposits of the Cromer Forest-bed Formation (sensu stricto) in Northeast Norfolk, in which the "West Runton Elephant" was uncovered, were deposited by the Ancaster River, or possibly a right-bank tributary.

Wroxham Crag and Norwich Crag

Further evidence concerning the relationship of the Wroxham and Norwich Crags was obtained by trial pits at Dobbs' Plantation (Figure 1), a site previously excavated by the Geological Society of Norfolk (Cambridge, 1978a,b). Cambridge recorded the bivalve Macoma baltica, indicative of the Pre-Pastonian stage, coming in about a metre above the base of the section, suggesting that here Pre-Pastonian Wroxham Crag might be resting upon earlier Norwich Crag. Our initial excavations at the site revealed only one gravel band, in the upper part of the sequence. On analysis this proved to contain (in the 8-16mm fraction) 82% flint, 12% quartz and quartzite, 6% Crag ironstone, 0.4% Carboniferous chert and 0.2% igneous and metamorphic rock, confirming that it did indeed belong to the Wroxham Crag Formation. Fortunately, we found a basal gravel in the Crag resting upon Upper Chalk at Old Hall Farm, Wroxham, only a kilometre away from Dobbs' Plantation, and on analysis this revealed (in the 16-32mm fraction) 90% flint and only 1.1% quartz and quartzite. This is typical of the Norwich Crag, since the Westleton Beds at Wangford yielded 1.17% quartz ands quartzite in the 16-32mm fraction. Thus in the Wroxham area, the Wroxham Crag rests upon thin Norwich Crag.

The Wroxham Crag may be observed in cliff sections along the north Norfolk coast, from Weybourne eastwards, and always resting directly on the Upper Chalk. It is typically dominated by gravel, with a large percentage of quartz and quartzite as well as well-rounded flints (Briant et al., 1999). Beds of marine bivalves, including Macoma baltica, are common. At Weybourne the Crag rests upon soliflucted Upper Chalk, with rounded clasts of chalk and angular flints embedded in a sandy chalk paste. Since this solifluction deposit must be older than the Pre-Pastonian Wroxham Crag, it was most likely formed during the Baventian cold period, implying that this area was land at that time, just before the Wroxham Crag transgression.

Having established the Wroxham Crag Formation in Norfolk, we returned to further investigate the Suffolk sections, since we had not suspected the existence of the Wroxham Crag when we wrote Hamblin *et al.* (1997). At Reydon and Covehithe, Mathers and Zalasiewicz (1996) recorded offshore sands and gravels overlying the beach-face Westleton Beds, implying a further transgression. We examined the gravel overlying the Westleton Beds at Covehithe, and found that it did indeed contain large quantities of vein quartz and quartzite. Thus we conclude that the transgression following formation of the Westleton Beds is in fact the Wroxham Crag transgression, demonstrating that the Wroxham Crag is present from the north coast of Norfolk at least as far south as northern Suffolk. Also, since the formation rests on a relatively late unit of the Norwich Crag (Baventian Westleton Beds) at Covehithe, on much earlier Norwich Crag (?Antian) at Dobbs' Plantation (only about a metre above the base of the formation), and on Upper Chalk at Weybourne, it can be seen that the unconformable base of the Wroxham Crag cuts down to rest on steadily older strata towards the north or north-west.

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LECTURE

Ordovician Soom Shale fossils, and early diversification of marine life

Summary of lecture presented to the Society on Saturday 11th November 2000 by Prof. Richard Aldridge, of Leicester University

Preservation of the soft tissues of animals in the fossil record is very rare, and new finds inevitably attract wide attention. The recent discovery of exceptionally preserved fossils in the late Ordovician Soom Shale of South Africa has special significance, as it provides the only known Ordovician deposit with fossil preservation equivalent to the celebrated Cambrian occurrences in the Burgess Shale of Canada, at Chengjiang in China and in the Scandinavian Orsten nodules.

The Soom Shale Member is a 10-15 m thick argillaceous unit within the 3000 m of arenites that make up the Cambrian-Silurian Table Mountain Group of the south-western Cape Province. It is of latest Ordovician (Ashgill) age, and comprises organic-rich, thinly laminated siltstones and mudstones laid down in a quiet-water marine basin, perhaps close to a retreating ice front. Sedimentological, geochemical and fossil evidence indicate that the bottom waters were dominantly anoxic and at times euxinic, with brief periods of oxygenation. The fauna of the Soom Shale is characterised by nektonic and nektobenthic species, including large conodonts, fish, orthoconic cephalopods and various arthropods; the cephalopods are commonly encrusted by lingulate brachiopods and cornulitids. Chitinozoans are abundant, and many bedding planes are covered with swirls of algae. The non-biomineralised tissues of several organisms are preserved in 3-D, including musculature and eye capsules of conodonts, musculature and respiratory structures (including book-gills) of eurypterids, pedicles of brachiopods and radulae of cephalopods. A particular feature of the biota is the presence of a number of bizarre, entirely soft-bodied animals that currently defy classification. The occurrence of coprolites containing crushed brachiopod shells or fragmentary conodont elements testifies to the presence of large predators or scavengers.

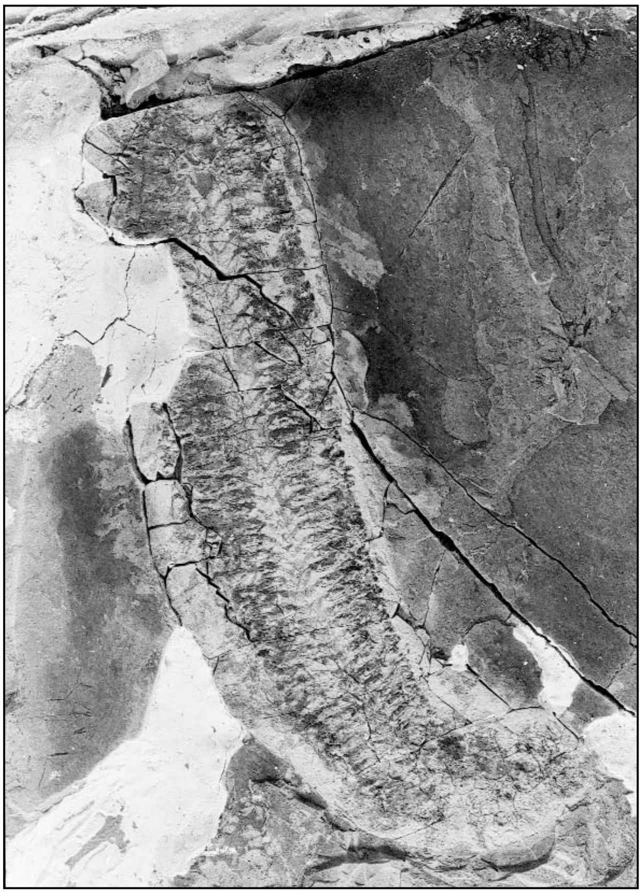

Figure 1. Enigmatic bilateral soft-bodied animal from the Soom Shale at Keurbos, near Clanwilliam, South Africa; x 0.3, presumed anterior at top. Body consists of more than 40 samarate (W-shaped) segments and is fringed on each side by a set of lobate appendages.

The anoxic and euxinic conditions in which the Soom Shale was deposited destroyed the skeletons (of $CaCO_3$ and $CaPO_4$) of all the fossils, but aided the preservation of soft tissues by inhibiting scavengers and burrowers and by promoting the depostion of authigenic clay minerals. These, now converted to illite, replaced soft tissues of animals as they decayed and also replaced the skeletal hard tissues as they dissolved away. Excellent replication of the soft tissues, as shown by the conodonts, eurypterids and several enigmatic organisms, shows that mineralisation occurred very soon after the death of the animals.

The occurrence in the Soom Shale of several organisms that resemble taxa otherwise only known from exceptionally-preserved Cambrian biotas suggests that some unusual body-plans may have had greater longevity than previously realised. It is also possible that some undescribed body-plans may represent experiments that were entirely Ordovician. These discoveries will help us to test models for early Palaeozoic evolutionary patterns that are currently influenced by data only from the Cambrian Lagerstatten.

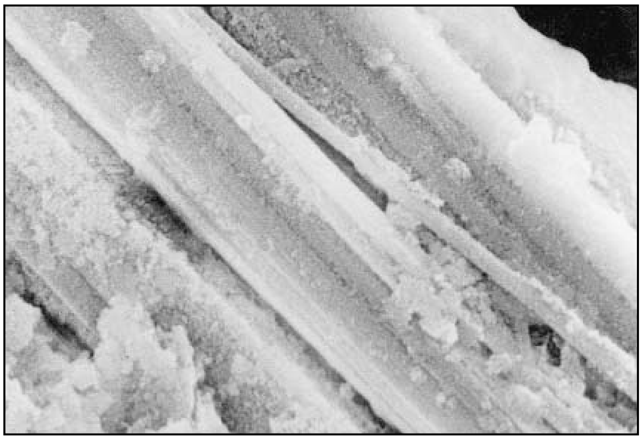

Figure 2. Muscle tissue from the body of a conodont animal in Soom Shale at Sandfontein, near Citrusdal. The muscle fibres and their myofibrils are replaced by illitic clay minerals; the fibres are about 5 mm across.

LECTURE

Hayfever in the Palaeozoic: reproductive strategies of lycophytes

Summary of lecture presented to the Society on Saturday 10th March 2001 by Dr Alan Hemsley, of Cardiff University.

The Lycopodiopsida (club mosses) arose in the late Silurian and early Devonian and, like other plant groups, began to diversify as part of the adaptive process of terrestrialisation. Like all early land plants, the club mosses reproduced by the dispersal of spores that were small in size and easily distributed by air currents (Burrows, 1975). Although probably not allergenic, the shear volume of small spores produced by Palaeozoic land plants was impressive. These spores were part of a reproductive cycle that arose as a result of the alternation of generations (diploid and haploid) presumably inherited from algal ancestors. Simply, mature diploid club moss plants (sporophytes) would produce haploid spores that germinated to give diminutive haploid plants (gametophytes) which in turn would produce male and female reproductive apparatus. Male structures (antheridia) would produce sperm that would swim in a film of water to the female eggs (archegonia) where they would then fuse to form a zygote (diploid again). This would then grow into a new club moss plant (sporophyte) to repeat the process. We can be confident that these plants followed this sequence because it is exactly how living pteridophytes such as ferns, horsetails and surviving club mosses reproduce today.

Reproduction by small spores is efficient as demonstrated by the abundance of living pteridophytes despite a wealth of competition from seed plants. However, pteridophytes such as club mosses are restricted in their possible habitats by the requirement of that film of water for the swimming sperm during reproduction. Inevitably, as land plants flourished through the Palaeozoic, so competitive evolution led to the exploration of possible means by which the pteridophytic mode of reproduction could bypass the need for abundant substrate moisture. The first major development to escape constraint was heterospory.

Heterosporous pteridophytes produce two types of spore; small male spores much the same size as ordinary wind dispersed spores (30-80 mm), and large female spores that may reach 2 mm or more in diameter. These spore types give rise directly to sperm in the case of the male while the large female spores split open along predefined lines of weakness to expose archegonia within. Although this process still requires a water film for sperm transit, many other features of the pteridophyte reproductive cycle have been minimised. In both the male and female, the gametophyte plant is largely retained within the protective coat of the spores and only the sperm has to brave the external environment. The female megaspores (Fig. 1a and b) are large because they contain food reserves for the rapid development of young sporophytes once their eggs are fertilised. This helps to speed up the reproductive process. Thirdly, there are many examples where we find the small spores of a club moss species attached to the outer coating of megaspores of the same species. This method, by which females carry males with them, must surely assist in the likelihood of fertilisation and minimise the distance over which the sperm must swim to achieve this. It is the adaptations of the spore coatings for small spore capture and the dispersal of the megaspore that made these large spores a particular nasal and skin irritant.

Heterosporous club mosses were abundant in the Carboniferous and at this time, many forms had evolved that had attained tree-like proportions. These produced a rain of both small spores and megaspores. Tree club mosses was able to disperse spores over a greater distance but some forms produced wing-like modifications of their coatings that enabled them to travel even greater distances. The flange-like wings effectively reduced their density and the speed with which they fell.

Other megaspore types (e.g. Lagenicula) may have evolved to achieve minimal dispersal. These were spiny with an aerodynamic extension to the apex of the spore. They perhaps fell directly to the ground beneath the parent plants that grew in dense dark swamp forests. This would have been a useful strategy where the parent was monocarpic (it died after spore production) since the death of the parent would provide a gap in the canopy and an increase in the available light immediately above the sporelings. These monocarpic tree club mosses posed additional airborne irritation besides their spiny megaspores. With these and other club mosses, spores were produced in small packets (sporangia) which were borne in association with a scale-like leaf. These scale leaves were usually aggregated into cones borne at the ends of branches. Once the spores were shed from the sporangia, the cones would have disintegrated, releasing the sharp scales to fall to the ground.

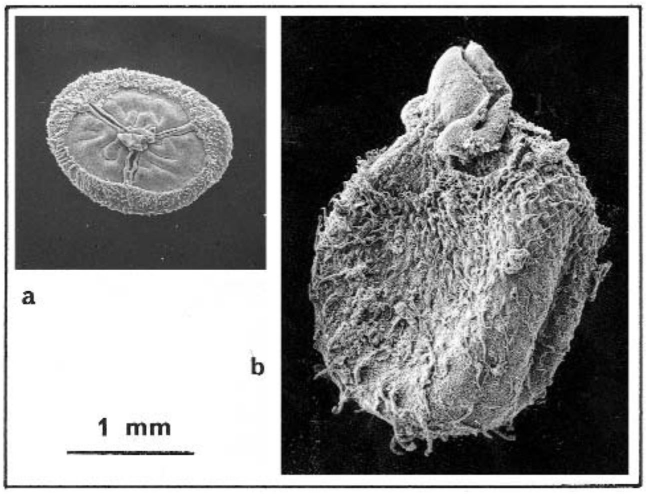

Figure 1. a) *Setosisporites brevispinosus*, a typical Carboniferous club moss megaspore. b) *Lagenicula crassiaculeata*, one of a number of species of megaspore produced by tree club mosses.

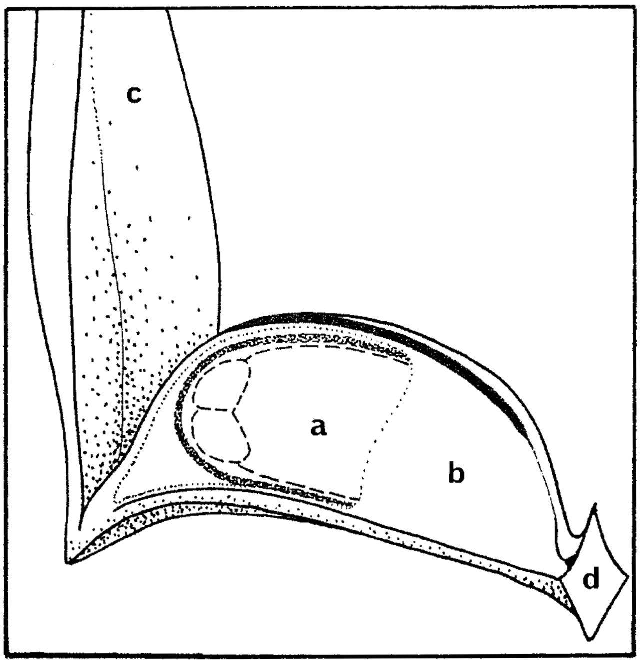

Figure 2. The Lepidocarpon reproductive unit, consisting of a megaspore within a sporangium (a) enclosed by extensions of the scale-like leaf (b) that also extended as a wing-like projection (c) beyond the sporangium. These were attached to a central axis at (d).

All of these megaspore-bearing plants, despite their abundant success (they form much of the plant material constituting the Carboniferous coal measures), were still restricted by the requirement of a water film for the passage of sperm to egg. One form of tree club moss, however, adopted a more extreme strategy. The cone known as Lepidocarpon was unusual in that the sporangia within only contained one functional megaspore of enormous size (up to 11 mm). Furthermore, the sporangium was enclosed almost completely by two extensions of the associated scale-like leaf (Thomas, 1981). This unit (Fig. 2) was therefore dispersed in its entirety; scale, sporangium and spore all together. One reason for this may have been that the attached scale could have aided dispersal by acting in much the same way as the wing of a sycamore seed. Laboratory experiments utilising models of 'lepidocarps' suggest that this was indeed a factor and also demonstrated how dangerous these sharp-scaled falling units would have been (Habgood et al., 1998). However, the most important function of the enclosing scale may have been to selectively collect male spores for fertilisation of the female, directly from air currents.

Figure 3. The floating position of 'lepidocarps', on their sides, where the slit along the top permitted fertilisation from spores and sperm at the water meniscus.

If this were the case, then Lepidocarpon behaved in the same way as seed plants that capture pollen from the air flow to fertilise an ovule (Crane, 1986). This method of male spore capture and delivery directly to the archegonia of the female spore eliminated the need for a film of water and thus enabled Lepidocarpon and its descendants to colonise drier habitats along with the seed plants that had already established a foothold in these areas.

Sadly, however, it seems that 'lepidocarps' were not fertilised by male spores captured from the air whilst they were still attached to their cones. Instead, they appear to have been even more reliant upon water fertilisation than some of the conventional megaspores. Laboratory experiments suggest that, following dispersal, 'lepidocarps' floated on the surface of local water bodies in such a way that the small opening left between the enclosing leaf scale extensions was in the perfect orientation to collect male spores and sperm from the water meniscus where they too had been shed or released (Habgood *et al.*, 1998, Fig. 3). This method of fertilisation matches our understanding of Carboniferous swamp ecology, but rather diminishes the status of Lepidocarpon as the club moss that almost became a seed plant.

There can be little doubt that, during the Carboniferous, the club mosses achieved a startling degree of diversity and that 'Lepidocarpon' is an advanced reproductive structure that crowned this age of pteridophyte exuberance. The seed plants, however, were already exploring drier habitats with their sophisticated pollination mechanisms and would go on through the Mesozoic to become the dominant land plants. None the less, in the dark swamp forests of the Palaeozoic, the club mosses thrived and to have ventured into such places (if one could) without a face mask and robust head protection would have been unwise indeed.

The author thanks Prof. Barry Thomas and Dr Kate Habgood for their assistance in laboratory experiments involving 'lepidocarps'.

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LECTURE

Kamchatka: volcanic wilderness

Summary of lecture presented to the Society on Saturday 14th October 2000 by Dr Tony Waltham, of Nottingham Trent University.

The Kamchatka peninsula, on the east coast of Russia, has a line of active volcanoes over the plate boundary where the Pacific Ocean floor is subducted beneath the continental plate of Siberia. It is the link between the volcanoes of Alaska and the Aleutians with those of Japan and the Kuriles.

Petropavlosk is the only town on Kamchatka. It stands against Avacha Bay, a magnificent natural harbour that is the home of Russia's Pacific fleet of nuclear submarines. Consequently Kamchatka was a closed area through the long years of the cold war, and its volcanoes were little known - except for the occasional major eruptions (of Bezymianny in 1956, and Tolbachik in 1975). The wane of the Russian military has now made visits to Kamchatka possible for westerners, and some volcanoes near Petropavlovsk are now accessible.

The twin cones of Koryaksky and Avacha rise directly above the back of Petropavlovsk. Both are classic andesite volcanoes with explosive eruption habits. About 30,000 years ago, the flank of Avacha failed, causing an enormous lateral blast towards the bay. The associated debris avalanches left boulder-grade deposits that are 150 m thick beneath parts of the modern city. Koryaksky is a comparable volcano, 3456 m high, currently dormant with only summit fumaroles and its last pyroclastic flows 45 years ago. A flank collapse is likely some time in the future, and will destroy a huge urban area. Avacha has its old open-sided crater now almost filled by a symmetrical cone. A walk to the top, 2741 m above the bay, provides a spectacular but energetic hike. Its crater was filled with lava in 1991, but fumaroles and solfataras are still active.

North of Petropavlovsk, the Valley of Geysers is Kamchatka's big tourist site, cut into the perimeter of the Uzon caldera, deep within the Kronotsky Nature Reserve of immaculate tundra. It usually pulls in about 50 visitors a day - which is two helicopter-loads on the only way of getting there (short of walking for a week). Boardwalk trails lead past a host of geothermal features. The Fountain Platform is a splendid bank of steaming geyserite with more than 100 geothermal vents - cyclic geysers, continuously fountaining spouters and simple fumaroles. It is claimed as the world's greatest concentration of geysers, but none erupts to more than a few metres high. Not far from it, the Velikan (Giant), Bolshoi (Big) and Malyi (Small) Geysers erupt to heights of 25, 10 and 8 m respectively. Cycle times on the steamy Bolshoi and the oblique fountain of Malyi are short enough that visitors can rely on seeing at least one eruption on their fly-in visit. The Valley probably ranks as the world's number two geothermal area at present (but it is a long way behind Yellowstone). An added bonus to the visit is the fly-past of Karimsky, a perfect andesitic cone whose Strombolian eruptions are so frequent that the helicopters circle the summit until it performs.

South of Petropavlovsk, Gorely is a classic basaltic volcano. Parasitic cones and old aa flows drape a broad shield that sits inside a shallow caldera, and its deep summit craters contain a cold one with icebergs from a small crater glacier, and a hot lake with steaming acidic water. Next to Gorely, Mutnovsky is a huge complex andesitic volcano. Its summit is swathed in glaciers, but the western slope is broken by a caldera that has its lower wall breached by a deep snow-floored gorge. The walk into this is magnificent. Walls of coarse pyroclastics are laced with dykes, and the caldera floor has glaciers spreading across it from the summit. These melt away just short of the caldera wall where they encounter geothermal heat. Steam jets and boiling mud pools lie in front of the ice, and steam plumes from deep crevasses belie more hidden fumaroles. A flank crater produces a steam plume hundreds of metres high from a wall fizzing with fumaroles and solfataras. Its last eruption was in 1960, and (until its next) it provides a splendid volcanic wilderness.

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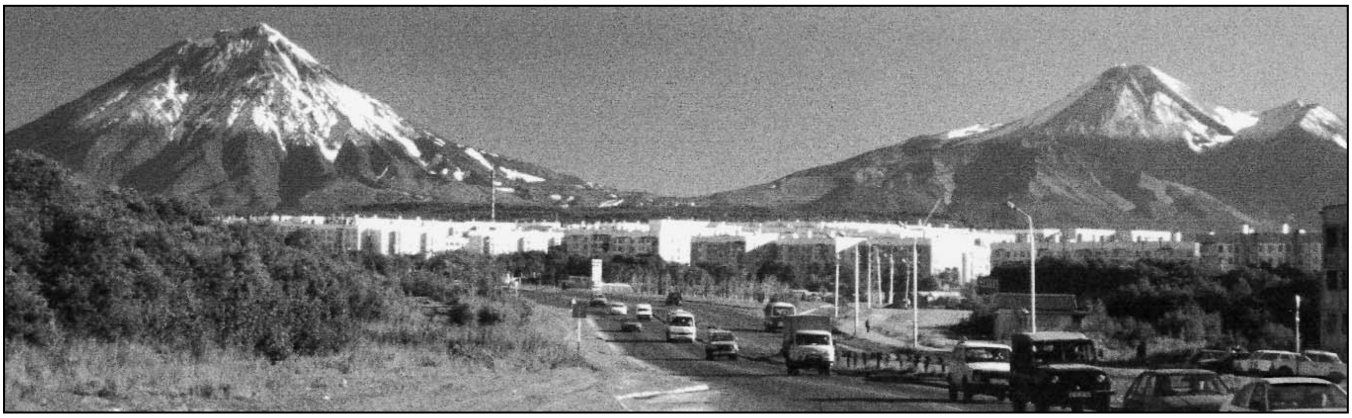

Koryaksky (left) and Avacha (right) seen above the outskirts of Petropavlovsk. The modern cone of Avacha sits inside the incomplete rim that remains after its ancient flank collapse.

EXCURSION

Birchover sandstones

Leader: Ian Chisholm (BGS)

Sunday 14th May 2000

The excursion involved a short walk to six sites around Birchover, on the eastern fringe of the Derbyshire Peak District. All sites were in the Namurian Ashover Grit, but any thoughts that this was just millstone grit were quickly dispelled by Ian's story of the unravelling of the mysteries of some of the hillside strutures.

Ian described how the Ashover Grit was indistinguishable from the other gritstones in the area, except that cross-bedding indicated that its formative river had flowed from the southeast, contrary to flows elsewhere that had been from the north. It seems that the distributary river had originated from the north, before being deflected by high ground, perhaps around Charnwood.

Ian's main challenge as a BGS surveyor was to explain a discordant ridge of sandstone that is cross-bedded at the base but massive at the top. One theory was that the contrasts were caused by faults, but others interpreted the ridge as a channel structure. Funding was found for two boreholes, one on the top of the ridge and one at the base, and these proved that the ridge was underlain by a rotational fault. The structures remained a mystery until Ian chanced on a paper with air photographs of similar structures in cliffs on Svalbard (Edwards, 1976). He then interpreted the Birchover structure as a large syndepositional slump scar that was filled with river sediment as it formed by collapse of the delta front. The local evidence and the unravelling of other fault slump structures nearby were described as the walk progressed.

1. Stanton Moor, 244628. The Stanton Syncline was viewed as a shallow fold on the eastern side of the Derbyshire Dome. Limestone underlies the syncline, and rises to outcrop to the north, west and south. The fold core contains about 250 m of Namurian sediments with dark mudstones below and sandstones above. Typical, cross-bedded Ashover Grit from near the top of the exposed sequence is seen in a quarry near the road.

2. Harthill Moor, 227623. Natural crags expose a thick massive lithology, in contrast to the cross-bedded sandstone seen on Stanton Moor. The conspicuous ridge at Birchover, extending down from the skyline, is clearly discordant to the simple structure of the syncline, and is formed by the slump structures that Ian had recognised.

3. Rock House, 233619. Exposures on the Birchover ridge are of the massive lithology. The view east overlooks dip-slope topography formed by undisturbed beds on the fault's upthrow side.

4. Birchover ridge, 238622. At the toe of the ridge, massive sandstone has a steep eroded contact above cross-bedded sandstone. Higher up, thick massive sandstone is well exposed in Druid's Rocks with a vague dip to the south.

5. Birchover quarry, 242624. The quarry faces may be seen from the road. Massive lithology dominates again, but bedding planes and dips are more obvious. From the quarry car park the borehole sites may be related to the cross sections through the ridge. It is clear that the massive facies that yields ‘dimension stone’ is thick only on the downthrow side of the slump fault, so there is a limited supply for quarrying.

6. Top of Stanton Moor, 247627. Normal cross-bedded sandstone in small quarries (and at site #1) must overlie the massive sandstone of the ridge.

Literature

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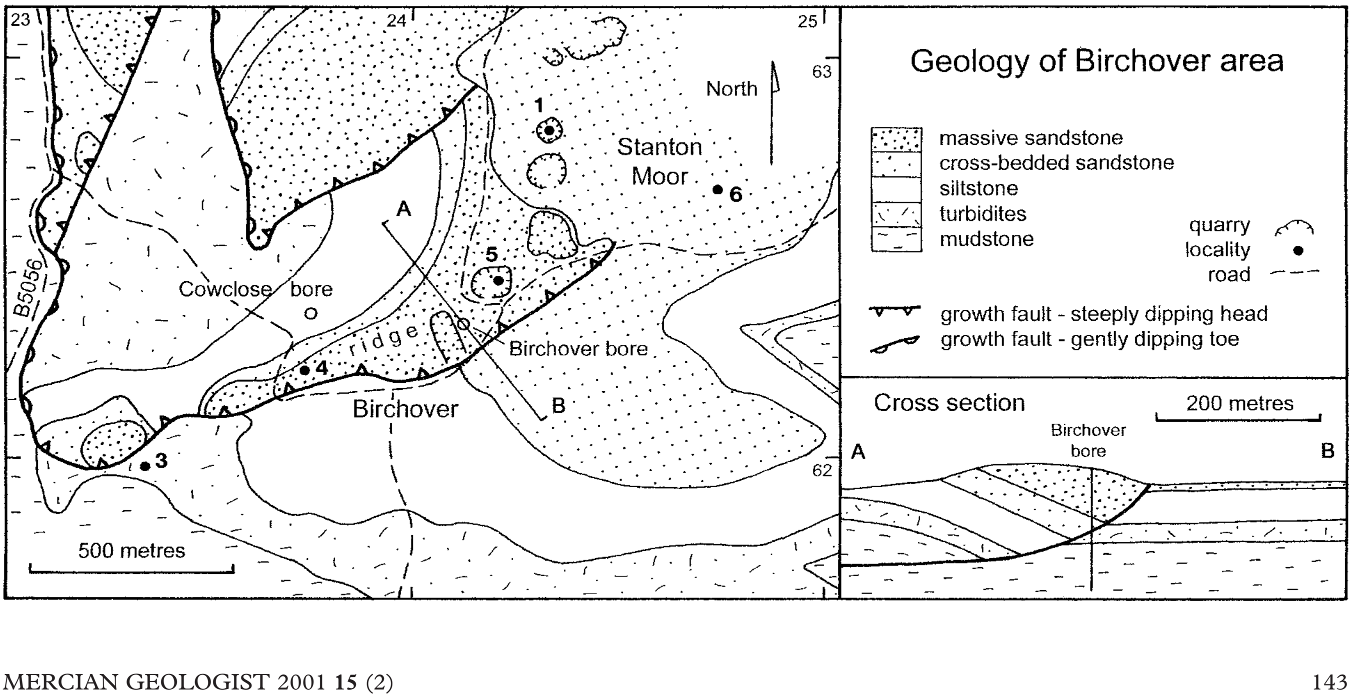
Alan Filmer (from notes by the leader)



EXCURSION

Carsington and Harboro'

Leader: Neil Aitkenhead

Sunday 16th July, 2000

Carsington Water

The day began at the Carsington Water Visitors Centre (SK245515), at the southern end of the Derbyshire Peak District. In a lecture theatre filled with an excellent turnout of members and guests, Neil described the geology and engineering story behind the failure of the original Carsington dam.

In June 1984, a part of the upstream side of the nearly completed dam, about 500m long and 37m high, progressively slipped. Fortunately the reservoir had not yet filled with water, for this could have led to a major disaster. The subsequent investigation (Coxon, 1986) found that "the predominant element in the slide was progressive failure arising from brittleness of the soils and geometry of the section. The weak ‘yellow clay’ foundation and the existence of solifluction shears within it were also contributory factors to the failure as it occurred". In other words, the design was poor and the site investigation inadequate! Some internal movement would have taken place naturally as the dam compacted under its own weight and this movement seems to have developed progressively into the disastrous slide.

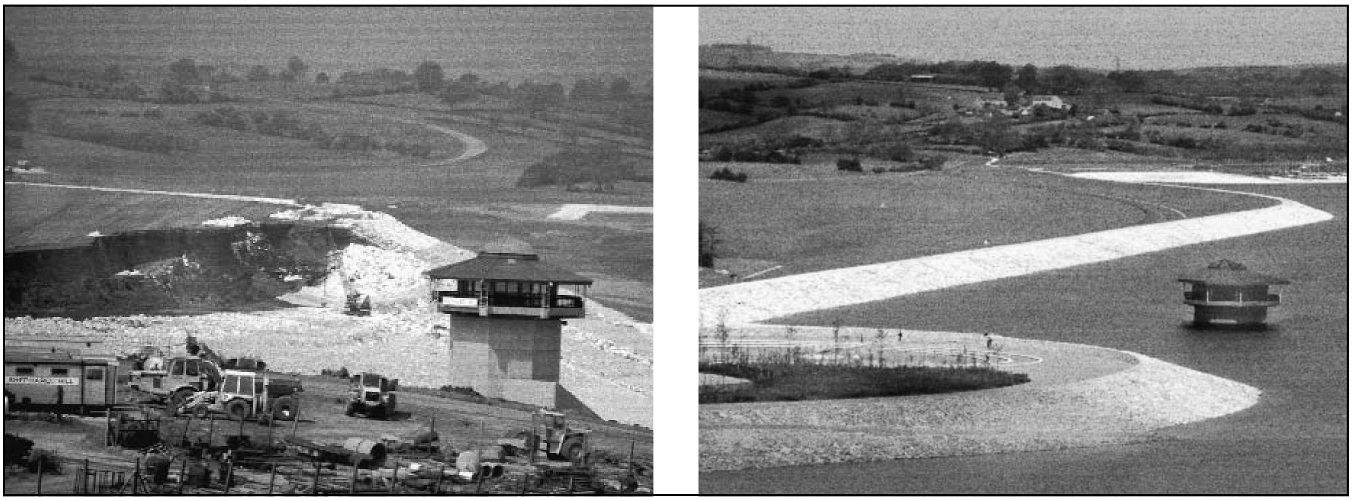
The site is underlain mainly by dark grey shaly mudstones, of the Namurian Edale Shale Group. Some thinly interbedded sandstones and siltstones occur, together with minor ironstones and impure limestones, a bed of cherty siltstone and a few laminae of altered volcanic ash. Marine bands occur at intervals throughout the succession. Key species of the goniatites and bivalves, and their subsequent identification by Dr Nick Riley, proved essential in making an accurate geological map of the site and delineating structural features that needed attention during dam construction.

The mudstones have been weathered near the ground surface to a pale brown clay, and this has been mobilised by solifluction in freeze-thaw periglacial conditions to produce a thin but extensive layer of head immediately beneath the topsoil. The only natural material directly implicated in the failure of the dam was the thin deposit of head. This was known only as the 'yellow clay' to the engineers, and was left in place beneath an extensive area of the embankment. There appears to have been no recognition of the presence of head in the pre-failure site investigation reports. The head was shown to contain weak clay minerals, and David Norbury, of Soil Mechanics, found relict shear planes that had developed during deposition.

Additional problems at the site, investigated by Dr Keith Ball, arose from oxidation of pyrite that was common in the shaly mudstones. Within the embankment porewaters, this produced sulphuric acid that reacted with incorporated limestone to produce gypsum and CO_2. Tragically, the accumulation of this gas caused the death of four men by asphyxiation in an inspection chamber.

Before rebuilding the embankment dam, the underlying head was removed. The clay core of the new dam has a wedge-shape in place of the original boot-shape. Embankment slope angles were reduced, and the reactive internal limestone drainage blankets were not replaced. Completion of the new dam, by September 1991, added tens of millions of pounds to the final cost.

Lunch was taken in Carsington village at the Miner’s Arms, after those stranded by hydraulic failure in their coach were ferried by colleagues with cars. From the village we walked north onto the limestone, up the hill towards Harboro' Rocks.



The southeast end of the Carsington dam, on the left immediately after the 1984 failure, and on the right after rebuilding, with the reservoir filled. The bulk of the dam is formed of dark mudstones, with the water face covered by light coloured limestone riprap, for protection against erosion.

Bee Low Limestone

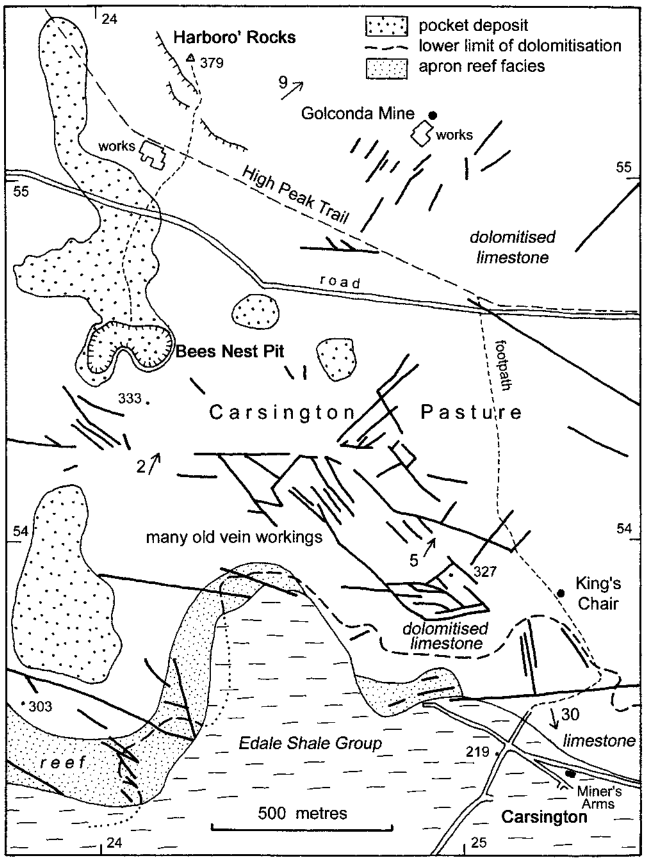
Undolomitised Bee Low Limestones exposed on the lower slopes were interpreted as shelf facies from near the southern margin of the Derbyshire Carbonate Platform adjacent to the subsiding Widmerpool Gulf. The question was raised as to whether it was indeed shelf or apron reef facies. Dave Mundy and Peter Gutteridge, both carbonate sedimentologists, noted that the limestones were mainly fine-grained micrite and showed a typical 'reef fabric' with irregular laminations of fibrous calcite cement. These were originally the linings of numerous cavities, which became flattened subparallel to the bedding during compaction of the lime mud. Dave noticed that the orientation of this fabric seemed to vary randomly from exposure to exposure, suggesting the presence of discrete, variously orientated blocks, reminiscent of the boulder beds at the foot of other apron reef slopes in the Peak District, at Castleton and Chrome Hill. It was agreed that these were tentative findings and that more work was needed, particularly on identification and measurement of the orientation of geopetal cavity fillings.

Mining

Further up the slope onto Carsington Pasture it soon became evident, from the number of old spoil heaps and capped shafts, that the ground had been intensively worked for minerals, mainly galena for its lead. Some minerals from these ores were seen where spoil had been disturbed by rabbits. The discovery of four Roman lead ingots at Lutudarum, now submerged by Carsington Water, suggests that local mining may well date back to Roman times (Willies, 1995).

Many of the spoil heaps are in lines over the veins. Others have a close-spaced but random distribution, probably over flats - orebodies that follow the carbonate bedding, perhaps just below the former shale cover. Other orebodies were developed at the base of the dolomitised limestone, notably at Golconda Mine.

The ores are thought to have been deposited by fluids that were derived from late Dinantian to early Namurian shales that were deposited in basins such as the Widmerpool Gulf, adjacent to the Derbyshire Carbonate Platform. By late Westphalian times, these shales would have been buried to depths of 2.5-3.0 km and, largely as a consequence, heated up to about 100-1200C. Additional heating may have been caused by the decay of radioactive minerals in the shale, and also by heat flow from volcanic centres. Thus the original porewaters in the marine sediments were transformed into hot brines, which became enriched in Pb, Ba, F, Cl, Zn and hydrocarbons. De-watering of the basinal rocks and the repeated build-up and release of crustal stress during fracturing and faulting of both basinal and platform rocks (seismic pumping) took place in the end-Carboniferous Variscan orogeny. By this mechanism, the ore-bearing fluids were moved from the source rocks to fracture planes and cavities in the host rocks, where the minerals were deposited by acid neutralization and sulphate reduction reactions during fluid mixing.



Outline geological map of the slopes from Carsington up to Harboro' Rocks. The limestone is dolomitised at outcrop, except in a narrow band adjacent to the shale.

The weather was splendid, and, as we climbed higher, so was the view to the south. We could see the Charnwood anticline in the far distance, Madge Hill in the middle distance and the west-facing escarpment of the Ashover Grit overlooking Carsington Water.

Dolomitisation

In the main limestone outcrops in the southern part of the Peak District, dolomitisation has clearly taken place from the top of the limestone downwards. The lower boundary with undolomitised limestone is sharp and greatly undulating, with up to 125 m of relief. Below the King's Chair, Neil demonstrated this with a series of sections from a limestone resource map of the area (Cox and Harrison, 1980). Dolomitisation occurred by the introduction of magnesium, presumably from percolating brines, into the calcite molecules. Dolomites tend to be open textured and vuggy. Although dolomitisation is reputed to cause a volume decrease of 12%, Dave and Peter pointed out that this only occurs under laboratory conditions. In natural conditions the decrease is much less, and subsequent dissolution of calcite remaining in the newly porous rock accounts for most of the typical vuggy character, specially on weathered surfaces.

The source of the magnesium-bearing brines and the timing of the main episodes of dolomitisation remain speculative. They may have occurred during the Variscan orogeny, when deep erosion in semi-desert conditions prevailed after considerable uplift. Brines from the late Permian Zechstein Sea have been considered a source, but evidence from the Permian rocks at outcrop to the east indicates that the nearest shoreline of that sea lay near Nottingham and the Peak District was a land area at the time. Saline ground waters circulating down from the Triassic Sherwood Sandstone, where that formation was in contact with the limestone, is another possible source (see below). Some of the mineralisation at Golconda Mine clearly post-dated both dolomitisation and the development of caverns at the dolomite-limestone boundary. Lesser episodes of both mineralisation and dolomitisation probably occurred up to Jurassic times.

The King's Chair (253538), a small isolated dolomite limestone tor adjacent to the path, looked as though it might have been artificially modified. Discussion led to no firm conclusion.

Further north, we crossed a broad dry valley (251542) with evidence of former excavations, perhaps in search of silica sand. An animal scrape displayed orange-brown silty loam containing glacial erratics that were mainly well rounded quartzitic pebbles derived from the Sherwood Conglomerate. Though shown on early maps of the Geological Survey as boulder clay, this deposit had been reclassified on the new map as head (Chisholm et al, 1988). Here it comprises a pre-Devensian till, that had become remobilised during Devensian periglacial conditions, moving down the slope and mixing with wind deposited loessic silt, to accumulate in the valley.

Harboro' Rocks

We followed the High Peak Trail, and then branched off to climb onto the top of Harboro' Rocks (243554). Here the question was raised as to whether these spectacular little cliffs are best described as tors, or are simply a craggy escarpment, like many others in the Peak District - though the processes of tor formation would have occurred regardless of terminology. The dolomite was perhaps initially subjected to deep chemical weathering in a warmer climate, particularly down major joint planes. Subsequent frost shattering and debris removal by gelifluction and wind erosion in Devensian periglacial conditions were probably also important. Fossils are commonly destroyed during dolomitisation but a few relic brachiopods and crinoids led to suggestion of an Asbian age for the sequence.

At the top, the topography of the southern part of the Derbyshire Carbonate Platform was beautifully displayed, and well-known landmarks were identified. Ian Thomas, from the Stone Centre, pointed out seven quarries, both active and abandoned, in both limestone and sandstone. Several factories visible on the plateau had at various times used limestone, dolomite and sand to produce cement, magnesium, refractory bricks and specialised ceramics. We could also see widespread evidence of former lead mining and some subsequent working for fluorspar.

Bees Nest Pit

We retracing our path to the High Peak Trail and headed south to the Bees Nest Pit (241546) - old excavations into a Pocket Deposit that was worked for silica to make refractory materials.

Pocket Deposits are preserved only in large, steep-sided solution dolines in the limestone plateau, but the succession that they represent (at least 45 m thick) must have been extensive in the area in Neogene times, on top of Namurian shales that rested unconformably on the limestone. The sands and clays are collectively assigned to the Brassington Formation. They have been dated as late Miocene to early Pliocene (perhaps about 7.0-3.5 Ma) from spores preserved in the grey clays of the Kenslow Member at the top of the succession. The clays are thought to have been deposited in a lake very close to sea level. The underlying sand-dominant Kirkham Member is deduced from palaeocurrent and petrographic evidence to have been deposited as alluvial fans emanating from a southward retreating escarpment of Triassic Sherwood Sandstone (Walsh *et al*, 1980), which now lies about 8 km to the south. Restoration of the sandstone escarpment, to the position it must have occupied during deposition of the Kirkham Member implies relative uplift of the limestone plateau by about 300m in the last 5 million years.

This was Neil's last field excursion before leaving us for Yorkshire. It was thoroughly enjoyed by all, and he was happy to see so many of his old colleagues. He has given a lot of time and enthusiasm to the Society, for which we are very grateful and we hope to see him again soon.

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Judy Small (from notes by the leader)

EXCURSION

The Lincolnshire Limestone

Leader: Alan Dawn

Sunday 8th October 2000

Three quarries between Duddington and Wansford, south of Stamford, were visited on a dry bright day.

First was the Bullimore's quarry at Duddington (at SK995013). The leader outlined the probable palaeogeography of these Jurassic limestones some 160 million years ago. The region was than at Mediterranean latitudes. Global climate was warmer than today, with no ice caps at the poles. Sea level was higher than it is at present. Deposition of the limestones was in a situation equivalent to that on the Bahama Banks today. Low lying land masses shelved gradually into shallow shelf seas, which gave way to deep water some distance from land. Terrestrial sediment input was small, and the carbonate was precipitated both by evaporation of warm sea water, and after its use by the molluscan fauna to build their shells.

Near to shore, silica sands were deposited, while further seawards, in water no more than 4-5 m deep, carbonate deposits accumulated along with some finer calcareous muds. At the seaward limit of the shallow shelf, wave action build an offshore barrier where moving water caused the formation of oolitic carbonates. Each oolith is a series of concentric spheres of carbonate around a small nucleus. Rolled by wave action, these ooliths eventually grew too heavy to be moved further, and were buried by the next generation of sediment.

Tidal fluctuations caused currents in the lagoonal area behind the off-shore barrier, so that cross-bedding and ripple marking is common. Localised channelling within the carbonates is ascribed to tidal scouring by currents related to breaches in the off-shore oolitic barrier. Long-term subsidence caused encroachment of the sea on to land, with the consquent landward migration of the oolitic barrier.

In the Duddington quarry, the lowest beds exposed are the Collyweston Slates, although the exposure was obscured by flooding at the time of the excursion. Collyweston "Slate" is a carbonate-cemented sandstone containing some mica, which aids splitting of the stone along the bedding planes. The quarrymen achieved this by leaving blocks of stone exposed to winter frosts, which left thin slabs that were trimmed by hand to form the slates.

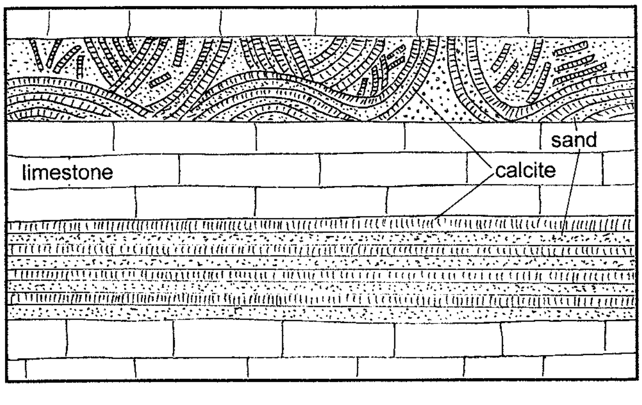

Figure 1. Alternating bands of sand and calcite, in units about 10 mm thick, some with contortions and some not, between beds of uniform limestone, in Crossley's Quarry.

The succession above the Collyweston beds becomes decreasingly siliceous and increasingly calcareous. It yields lignified wood and fossils of the fern *Phlebopteris woodwardii.*

Cross-bedding of the carbonates is prominent in some parts of the quarry, and has been measured by Prof David James. He has found that small to medium scale cross-bedding, of both trough and tabular type, shows wide variation in orientation, but 26 fairly reliable group-averaged readings from all three quarries show a 2:1 domination of flow in the NW-SE quadrants relative to the NE-SW quadrants. In both quadrants flow reversals, locally of herring-bone type, are abundant. No channel margins were seen. Together with the layer-cake stratigraphy, this suggests low-gradient, sinuous tidal channels migrating across and within the ooid bars. Flow variance is much less on the small scale, and at least three sets of local flow reversing can be seen in different areas of the Duddington quarry. There were sandy tidal flats, and back-barrier floodplains transgressed by ooid bars, which created their own lagoons with channels to the sea.

The second visit was to the Crossley's Quarry (at TF030006), operated by Bardon Roadstone. Here the exposure is not so deep as at the Duddington quarry. This is partly due to erosion and partly to the lensing out of the whole sequence of the Lincolnshire Limestone a few kilometres south.

The dominant feature at Crossley's is the de-calcification of the limestone, along with spheroidal weathering. The lower beds are strongly blue-hearted. The blue/grey colour is due to finely disseminated pyrite, FeS_2, which weathers to hydrated iron oxides that give the weathered rock its golden brown colour. More plant remains, and the fossil gastropod *Nerinea* were found. The weathering leaves spheroidal corestones - the quarrymen's *doggers*, from 200 mm to a metre or more in diameter, with horizontal bedding planes that can be traced through most.

Some strange thinly bedded structures remain an enigma. Beds of sand and calcite, each little more than 10 mm thick, are either horizontally bedded, or are contorted into curious structures (Fig. 1).

The final visit was to the Thornhaugh quarry (at TL058999). This extends deeper than the base of the limestone and exposes the sands of the Grantham Formation, previously known as the Lower Estuarine Series or the Variable Beds. Locally these are a pure silica sand with root beds and a few thin coaly horizons, some of which may represent wild-fire events. They have been used to make refractory products. The limestone beds are entirely of the lagoonal back-reef facies. The lower levels are particularly rich in fossils of plant fragments, corals, bivalves and echinoderms. Some quarry faces reveal Pleistocene cryoturbation (see the report elsewhere in this issue).

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