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East Midlands Geological Society

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Cover photograph: The landslide at Mam Tor, above Castleton in the Derbyshire Peak District, with the old main road that is now permanently closed due to the slide's continuing movement. See report on page 55 [photo: Tony Waltham].

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PROFILE

Tony Morris

With the election of Tony Morris as president of the EMGS in this millennium year, the Society comes very much down to earth! Tony was born in Nottingham during the hostilities of the Second World War. He was brought up and educated locally at Haydn Road Infant and Junior Schools and at Claremont Secondary Boys School. He continued his education at both Peoples College and Nottingham Regional College of Technology (now Nottingham Trent University) where he obtained his ONC and HNC in Building. He was initially employed by Thomas Fish & Sons (Building Contractors) as a Building/Assistant Quantity Surveyor and subsequently he joined the National Coal Board in their Architects and Surveying Department.

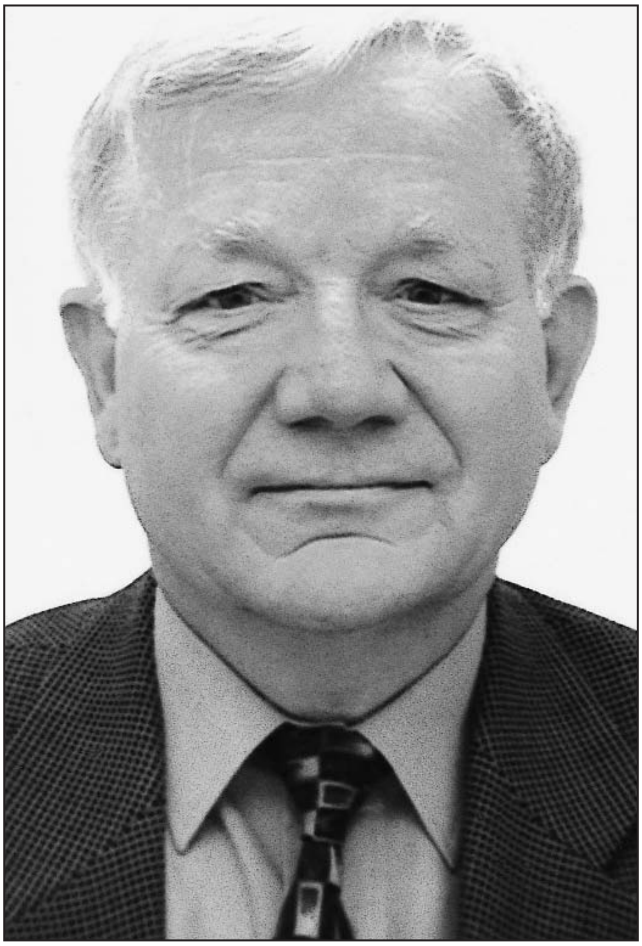
Employment at the Coal Board did not hold sway for long and service to and behalf of others soon beckoned. His interest and involvement in politics and trade union affairs led to him joining the National Union of Public Employees in 1964 as a full-time trade union officer.

Important changes to Tony's life came in 1966 when he married Jean and his work with N.U.P.E. resulted in a move to Lincoln where they lived for seven years. Promotion in 1973 to Assistant Divisional Officer saw a return to Nottingham. With the creation of a larger public sector trade union, UNISON in 1992/3, Tony was appointed as its East Midlands Regional Head of Health. After more than 30 years as a trade union official Tony took the opportunity for early retirement in 1995, enabling him to expand his interest and involvement with a variety of organisations.

Tony has always taken an active interest in local education affairs. For over twenty years he was the Vice-Chairman of the Basford Hall College of Further Education and he now serves on the Governing Body of New College Nottingham (an amalgamation of several local colleges of further education).

For five years prior to his retirement, Tony was a Director of the North Nottinghamshire Training and Enterprise Council, and he is currently a Non-Executive Director of the Central Nottinghamshire Healthcare N.H.S. Trust, and he serves as an Employment Tribunal panel member.

We would like to think that Tony's first encounter with geology was when, early one Sunday morning, he broke his toe when creating a rockery made of Bulwell Stone! However, in reality, his geological interests stem from his secondary school years with a love of physical geography and summer holidays spent with his aunt and uncle at Great Longstone, Derbyshire, collecting minerals and fossils from the Carboniferous Limestone.



His fascination with geology led him to attend, with his wife Jean, his first geology adult education classes in the 1970s, expertly tutored by Colin Bagshaw. His interest in geology mushroomed with further University and W.E.A. classes, numerous geological excursions and study tours in Britain, North America and Italy and membership of the E.M.G.S. in the late 1970s. Since his retirement he has also found time to serve as a Council member from 1996 to 1998, and he is currently a member of the Editorial Board of the Mercian Geologist.

Both he and Jean extended their interests in geology by undertaking a round-the-world trip in 1998 taking in some well known geological sites in Queensland, New Zealand and Hawaii.

His appreciation of geology does not curtail his interest in a variety of other subject areas through adult education classes and interest and involvement in the William Morris Society, the Cromwell Association, the Royal Society for the Protection. of Birds, the National Trust and the Nottinghamshire Wildlife Trust. In addition, Tony actively participates in local politics, and has a continuing commitment to the Labour Party.

With the election of Tony Morris as a non-professional geologist, the Society continues to promote the interests of both the professional and amateur geologist.

Andrew and Judy Rigby

MERCIAN NEWS

Wollaton Hall

A new mineral display opens at the Nottingham Natural History Museum at Wollaton Hall, on Friday, July 21st as part of the 'Green Wollaton Trail'. It is in the existing mineral gallery on the first floor of the museum within the Hall.

Featured are two new showcases of the more spectacular minerals, including fluorite, calcite, goethite, rhodochrosite and crocoite, together with a camera microscope and monitor to allow visitors to examine minerals under the microscope for themselves. The new display carries a 'green' message about the environmental impact of mining operations around the world, in particular, the damage being caused by gold mining to the rain forest environment in Brazil.

The museum is open every day from 11am to 5pm in summer, and daily except Fridays from 11am to 4pm in winter. Admission is free during the week, but there is a small charge at weekends.

Editorial

Items from Society members are always welcome for the Mercian News and for the Geobrowser column. All material, and any longer reports or full papers, should be sent to the editor, who will pass them on to the appropriate section sub-editor. The editor will also value any member's feedback or suggestions on the content of *Mercian Geologist*.

EMGS at Earth Alert

Earth Alert was a successful four-day Millennium Festival of Geology hosted by the Geologists' Association at Brighton in May 2000. The EMGS display stand was one among a hundred at the event, and was manned by Ben Bentley.

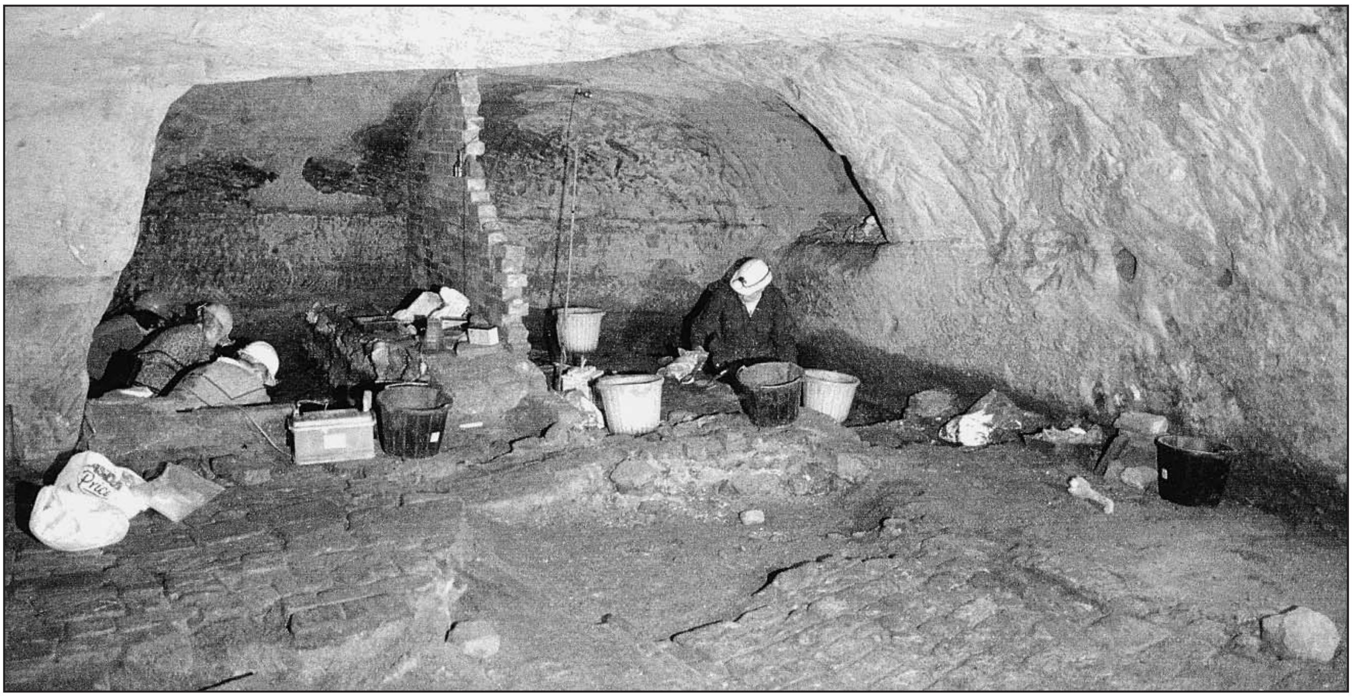
The four days had a continuous programme of lectures, there was a Rock, Mineral and Fossil Show, and two festival exhibitions occupied side halls. A big attraction for the younger visitors was a hands-on fossil programme run by Rockwatch, the Natural History Museum and the Open University. This included a race between radio-controlled trilobites of Paradoxidian dimensions (about 30 cm long) that had to be seen to be believed, and attracted more than a share of the older visitors

More and less caves

Excavations for the foundations of Nottingham's new ice stadium revealed twenty caves, of which only two had been previously recorded. Most had been cellars beneath houses, but there was also a cave malt kiln complex. Many of the caves had already been unroofed or damaged, and they are now all filled with concrete. At least their temporary exposure did add to the sparse cave records for the eastern end of the old town.

On a brighter note, a new cave has been found and preserved under the Broad Marsh Centre. Its entrance was exposed during excavation of the debris in the western caves. Ongoing work by archaeologists of the Nottingham Historical and Archaeological Society has exposed two splendid brick floors in caves that were once used as stables. The clearance effort is in preparation for extending the system of caves that is accessible to visitors.

Archaeologists from the NHAS at work in the western caves under the Broad Marsh Centre. They are digging beneath missing parts of the old brick floor to expose the original rock floor and any early artefacts.



GEOBROWSER

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

Global spin

The debate about global warming, and mankind's part in it, has been re-ignited following the Sir Peter Kent Lecture given by the Environment Minister, the Rt. Hon Michael Meacher, to the Geological Society and reported in the January Geoscientist. The Minister quoted figures, from British Government-funded research, showing that global temperatures have risen by 0.6oC over the last 140 years, and that man-made greenhouse gas emissions have made a quantifiable contribution to this increase within the last 50 years alone. The reported reluctance of some developed countries to implement certain of the Kyoto targets probably has nothing to do with the substance of a subsequent letter published in the March edition of *Geoscientist*. A mining exploration consultant based in Canada suggested that the Minister's speech was an example of 'non-science', and blamed the situation on sunspot cycles, which could promote warming by releasing large amounts of water vapour to the atmosphere. Meacher's stance was supported, however, by two communications originating from this side of the pond, in the May *Geoscientist*. These emphasised that current climate models have failed to explain global warming simply in terms of water vapour content or sunspots, indeed no model has been able to replicate the planet's warming over the last century - without taking into account the rising concentrations of greenhouse gases.

Global impact

It is difficult to pick up a modern popular geological publication that does not refer to a catastrophe, and it is equally difficult to deny that such articles make compelling reading. One of the remaining lines of research into the Chicxulub impact structure in Mexico, was to determine its third dimension. In 1996 this was finally accomplished following the acquisition of marine seismic deep-reflection profiles, coupled with onshore wide-angle seismic profiles. The results are spectacular (*Geology, 1999; p.407*). The impact structure appears to have consisted of a three-ring 'excavation cavity', of about 100 km diameter, beneath which there is a whole-crust deformation zone that includes significant offsets to the Moho at depths down to 55 km.

Apart from ridding this planet of dinosaurs, the Chicxulub impact has benefited us in other, more material ways (*Geology, 2000, p.307*). It effectively created the preconditions for the south-eastern Mexico oil fields, currently producing 1.3 million barrels per day. Firstly, the seismic impact loosened the substrate by shattering the platform limestone sequence that had been quietly accumulating at the end of the Cretaceous; this produced limestone-breccias, up to 300 metres thick, now constituting the principal oil reservoir. Next came the accumulation of a 30 m-thick layer of impact material, consisting of bentonitic clays with conglomeratic lenses representing the ejecta reworked by tsunamis. This upper layer effectively sealed the limestone- breccia reservoir from later diagenetic fluids, and prevented any possibility of hydrocarbon migration when eventually the oil was generated.

Sun, sea and slides

Reports of instantaneous events, such as comet strikes and the eruptions of 'supervolcanoes', seldom fail to enliven the popular media. Understandably less obvious are the major submarine 'catastrophes', involving single large debris flows that have ran out across the sea floor for distances of up to 400 kilometres. These are presently being discovered and investigated off the African continental margin, opposite the Saharan coast and Canary Islands (*Sedimentology, 1999; p.317*). The Canaries are steep-sided volcanic islands that built up fairly rapidly from the sea floor, and in consequence they have experienced their own, equally spectacular flank collapses. The example discussed in *Geology* (*1999, p.739*) should be of particular interest to those intending to visit the resorts of western Tenerife. It appears that the steep seaward slopes mantled by deposits from the intermittently active Teide Volcano are actually founded on much older breccias. These were formed over the past six million years, by several episodes of debris flowage. The origin of these debris flow events is linked to the genesis of the horseshoe-shaped wall of Las Canadas, which partly encircles Teide to the south-east. Rather than simply being the side of a caldera, this feature is primarily a type of composite, mega-landslide scar, formed by repeated lateral collapses of the pre-Teide volcanic edifice. The submarine continuations of the debris flow breccias have been detected by offshore sonar investigations, but the scale of their size in relation to the continental margin examples was not mentioned.

Minoan disaster?

The repercussions of sudden volcano-collapse events were drastically illustrated by the loss of life, and collateral damage, caused by the tsunamis generated when Krakatau exploded in 1883. But what sort of role has been played by similar catastrophes in the more distant past? It has long been known that the islands and coastlines of the Aegean Sea are fringed by tsunami-like deposits, and the temptation was to associate such tidal wave activity with the violent eruption of Thera, on Santorini, between 3000 and 4000 years ago. A major displacement of seawater, during the massive collapse that terminated this eruption, could easily have generated the tsunamis, but the linkage between these events had always been based on circumstantial evidence. Support for such a connection is now forthcoming, however, through work that has combined geology with archaeology and computer modelling of the eruption (*Geology, 2000, p.59*). Trenches dug in the Minoan ruins on the Turkish and Cretan coasts have revealed a two-layer stratigraphic record of the catastrophe, that begins with a thin tsunami deposit, identified by its fossils that include life-forms normally found far offshore. Directly overlying this comes the new find of a tephra layer, the ejecta of which matches material known to have come from the Plinian phase of the Thera eruption. In real-time, these Plinian eruptions actually preceded the volcano collapse that generated the tsunami. However, the tephra had to be carried by eruption clouds, and these probably took 2 to 3 days to reach the shores of Turkey. The tsunami travelled faster; it overtook the eruption column, and according to the computer simulation arrived on the Turkish coast only about 2.5 hours after it was generated. The demise of the entire Minoan civilisation has commonly been attributed to these events, but other studies are showing that although the Thera eruption was severe, Minoan life continued for some time afterwards.

NEWS from the BGS

Geoscience takes guts

Geochemists at the British Geological Survey are currently using synthetic stomachs to assist them with their work. This is not to provide a remedy for ‘over-indulgence’ during fieldwork, but to determine the risks to humans and animals from the ingestion of soils contaminated with metals.

Impending legislation will require local authorities to take responsibility for contaminated land within their boundaries and to assess the risks associated with the contamination. Current guidelines stipulate that risk assessments should be based on the total concentration of toxic substances in soils, although it is known that only a fraction of metal contaminants in soils is actually absorbed – or ‘bioavailable’ – via plants or animals. BGS is using synthetic stomach solutions at 37°C to determine the percentage of soil contaminants that are ‘bioavailable’ via uptake through the human gut. Using soils containing arsenic exceeding the recommended limit of 10 milligrams per kilogram, BGS tests have indicated that, in some cases, less than 1% of the arsenic is extracted from the soil by the stomach solution and would hence be absorbed following ingestion.

Research is continuing with other contaminants, and will lead to a better understanding of the toxicity of soils on contaminated sites. As pressure continues to mount on land use in the UK, this research will ultimately assist with assessing the health risks associated with contaminated land and will encourage its effective re-use with appropriate types of development.

Tsunami catastrophes

Britain’s coastline may be at risk from tsunamis, giant waves that can have devastating effects on communities in low-lying coastal areas. Marine geologists at the BGS are currently determining which areas could be threatened, quantifying the extent of the hazard and developing strategies for reducing the risks.

Tsunamis have been responsible for some of the most notorious catastrophes in history. Those following the eruption of Krakatoa in 1883 killed 30,000 people in the coastal zones of Java and Sumatra, and tsunamis devastated shores of the Mediterranean when Santorini exploded (see the note in Geobrowser). The most destructive tsunamis have been associated with earthquakes or island volcano eruptions, but recent research indicates that powerful tsunamis may also be caused by submarine landslides. These can occur along continental margins in many parts of the world, outside the earthquake and volcano zones. Large concentrations of the world's population live on coastal lowlands just a few metres above sea level and are therefore potentially at risk.

Submarine landslides result from failure of large volumes of sediment on continental slopes. They can be triggered by minor seismicity, by the release of shallow gas or the melting of gas hydrates (gas locked into ice molecules). Such landslides are known to have occurred along the continental margins of Northwest Europe. About 7000 years ago, a gigantic slide occurred at the northern end of the North Sea, displacing about 5500 cubic kilometres of sediments. This caused a tidal wave up to 5m high, inundating the coast as far south as Northumbria and depositing a layer of marine sediments that can be traced for up to a kilometre inland. The effects were even greater along the Norwegian coast. Other submarine landslides have been identified to the west of the island of Barra and along the Atlantic margin.

BGS has been investigating whether future landslides could pose a risk in coastal zones in the UK. The project is looking into the causes of submarine landslides and their frequency, calculating the possible heights of tsunamis and examining how the shape of the coastline may focus the wave effects. This will highlight vulnerable areas and provide planners and insurers with the information they need for risk assessment and management.

Publications go online

BGS is following the trend by offering its services and products online. The new e-commerce site at www.british-geological-survey.co.uk is designed for customers with credit cards to browse and buy online from the Survey's range of printed maps, books and guides. Selected photographic images and some key digital information such as the World Mineral Statistics can also be purchased.

Future development of the site will provide BGS customers with an ever-expanding range of geoscience services and information. More advanced products, such as digital map data, are planned for the near future, and in a third phase of development the site will offer interactive services for delivery of site-specific information.

Back in the land of paper, BGS is about to publish a new book in its *Earthwise* series entitled *Catastrophes – Time's trail of destruction*. Written by Susanna Van Rose and lavishly illustrated, the book investigates the origins of famous catastrophes since the dawn of creation.

FROM THE ARCHIVES

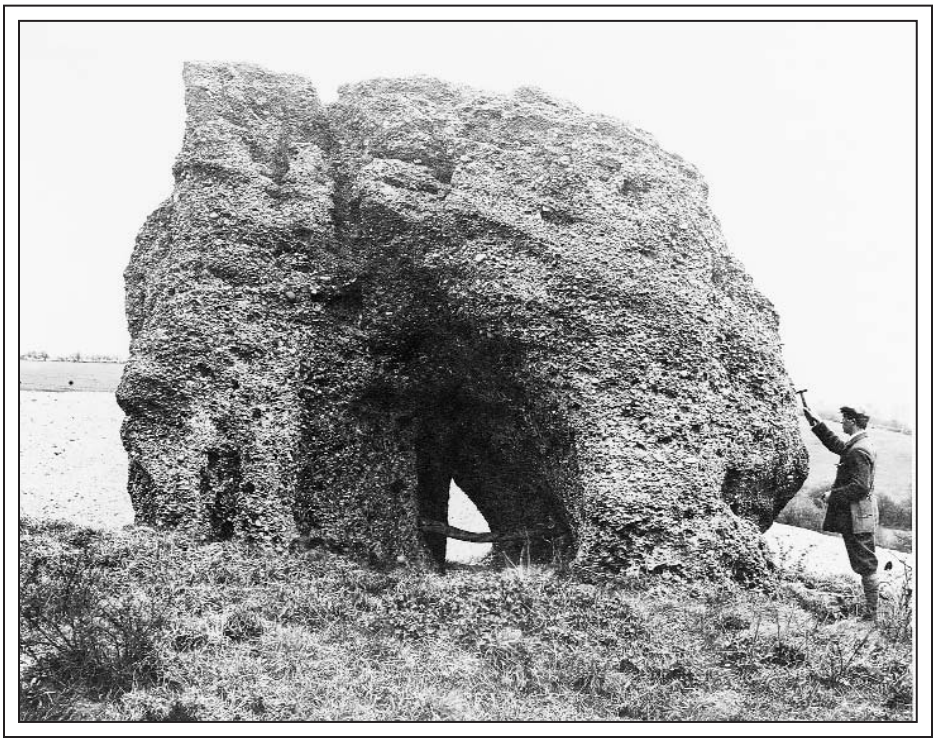
An archive photograph of East Midlands geology from the British Geological Survey collection.

Druids' Stone at Blidworth

This particular Druids' Stone stands on a sandstone slope (at NGR SK579558), just west of Blidworth in Nottinghamshire; it lies close to a footpath that heads west from near the old village church. Though marked on old maps as *Druidical Remains*, its name is hardly appropriate. The Stone is a calcreted mass of glacio-fluvial gravel, left behind after the surrounding uncemented gravels were quarried away. These gravels of the Blidworth area are remnants of a formerly more extensive sheet, that was deposited by meltwaters towards the end of the Anglian glaciation about 450,000 years ago. The pebbles are mostly sourced from local Triassic sandstones, but include erratics originating from the Lake District and from Jurassic and Cretaceous rocks of north-east England and the southern North Sea.

The image was taken on 24 April 1911 by Jack Rhodes, photographer for the Geological Survey of Great Britain, during survey of the Ollerton geological map. Jack Rhodes joined the survey as a young man in 1910, and soon became involved in geological photography, a job he held until his retirement in 1956. By this time he had taken over nine thousand photographs. In the early days he carried his equipment into the field using a horse or donkey, for which he received a hay allowance. He was later supplied with a motor cycle and sidecar, finally graduating to a motor car in 1945. Many of his early photographs used long exposure times which, along with lens aperture, location and weather conditions, were recorded in meticulous detail. The figure on the right of the Druids' Stone, while apparently hammering with gusto, must in fact have been holding his breath and standing still (or 'petrified' perhaps), as the exposure time for the photo was two seconds.

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



The Druids' Stone at Blidworth, as viewed from the west in 1911. Short of checking for individual missing pebbles, the rock looks exactly the same today (BGS photograph #A1175, © NERC).

Igneous processes within late Precambrian volcanic centres near Whitwick, northwestern Charnwood Forest

John Carney

Abstract. Precambrian rocks in northwestern Charnwood Forest differ markedly from their lateral equivalents to the east and south. They are subdivided into the Whitwick Volcanic Complex, of massive to intensely brecciated high-silica andesites and porphyritic dacites, and the Charnwood Lodge Volcanic Formation, which is a thickly bedded sequence of mainly andesitic to dacitic volcanic breccias and lapilli-tuffs. Lithological elements common to both of these units are indicated by field, petrographical and geochemical evidence, which suggests the existence of two 'genetic associations' of rock-types. These associations, and various other units that are distinctive to this region, form the basis of a model that views the Whitwick Complex as an aggregation of magmatic feeder bodies that supplied material, in the form of blocks and lapilli, to a volcaniclastic apron represented by the Charnwood Lodge Formation. The analogues for these rocks can be drawn from the axial magmatic zones of modern or geologically very young volcanic arc systems. The high-silica (dacitic and rhyolitic) Charnian magmas were intruded into unconsolidated wet sediments, resulting in physical interactions that generated peperitic lithologies and related breccias. By contrast, the andesitic magmas may have extruded subaerially as lava domes that periodically collapsed, giving rise to block and ash pyroclastic flows and lahars.

Throughout an exposed thickness of 3500 m, the Precambrian of Charnwood Forest is mainly a stratified succession, showing sedimentary features in keeping with deposition in fairly deep waters (Moseley and Ford, 1989). The accumulation of these strata at a time of active volcanism was nevertheless recognised long ago (Jukes *et al.*, in Potter, 1842; Jukes, 1857, summarised in Watts, 1947, p.121-122), and has since been confirmed by petrographic studies revealing that these rocks have a high content of pyroclastic material. The term 'volcaniclastic' is given to sequences of this type (terminology of Fisher, 1961; Fisher and Schmincke, 1984), which encompass a wide spectrum of clastic rocks composed in part or entirely of volcanic fragments formed and deposited by any mechanism. These fragments can be epiclastic in origin, consisting of abraded grains derived from the erosion of pre-existing volcanic deposits, or they can be of pyroclastic origin, derived directly from contemporary volcanic activity. These pyroclastic rocks may consist of euhedral crystals or angular crystal fragments, angular volcanic grains and non-abraded shards and scoria that were once glassy. Moseley and Ford (1985) gave the name 'Charnian Supergroup' to the stratiform rocks and it is the various subdivisions of the Maplewell Group that are among the main subjects of this account, together with another highly significant unit, the Whitwick Volcanic Complex, in the northwest. These divisions are listed in Table 1 in their stratigraphical and environmental context, and their outcrop areas are given in Figure 1.

The abundance of pyroclastic constituents in the Maplewell Group has prompted much speculation as to where the volcanic centres were located. Many previous workers have proposed the northwestern part of Charnwood Forest to be the most likely magmatic source area (e.g. Hill and Bonney, 1891), a suggestion which is supported by two types of lithological variation. The first of these is a spatial variation, which is developed on a regional scale within the Maplewell Group, and has an important bearing on the location of the Charnian volcanic source(s). It involves a lateral transition from the predominantly distal-facies volcaniclastic rocks that characterise the Beacon Hill Formation, in the south and east of Charnwood Forest, to a coarse-grained proximal facies sequence that is represented by the fragmental lithologies of the Charnwood Lodge Volcanic Formation (Fig. 1, inset). The latter unit is best developed in the present study area, where it is closely associated with the Whitwick Volcanic Complex, containing massive igneous rocks that may be the remnants of magmatic feeder bodies (Table 1). The second variation is temporal, and is reflected by the up-section increase in pyroclastic content from the Blackbrook Group, which largely consists of tuffaceous rocks (with 25-75% of pyroclastic constituents) to the Maplewell Group in which tuffs (with over 75% of pyroclastic constituents), or their reworked equivalents, are more abundant. This is significant because it means that the Maplewell Group – and hence the volcanic region of north-west Charnwood Forest - contains the youngest phase of Charnian volcanism. Clues to the environment in which this volcanism occurred are provided by geochemistry, reviewed more fully below, which indicates that these rocks originated within a volcanic arc tectonic setting. The late

Table 1. Lithostratigraphical summary of north-west Charnwood rock units, highlighted in bold, showing their relationship to the other major components of the Charnian Supergroup and their likely environments. The double-headed arrows link genetically related rock types that constitute the Grimley/Cademan association (1) and the Sharpley/Swannymote association (2).

BRAND GROUP (?Lower Cambrian)

Unconformity

CHARNIAN SUPERGROUP

WHITWICK VOLCANIC COMPLEX	North and west	South and east	
Units of the volcanic centres:	*Distal volcaniclastic strata:* Bradgate Formation	*Distal volcaniclastic strata:* Bradgate Formation	MAPLEWELL GROUP
	Proximal volcaniclastic units:		
	Charnwood Lodge Volcanic F:	Beacon Hill Formation:	
Genetic Associations:	**Undivided beds**		
	St. Bernard Tuff M.	various other units which include:	
Grimley Andesite ◄— 1 —►	**Cademan Volcanic Breccia M.**		
Sharpley Porphyritic Dacite ◄— 2 —►	**Swannymote Breccia M.**		
	Benscliffe Breccia M.	Benscliffe Breccia M.	
Peldar Dacite Breccia			
	Distal volcaniclastic strata of 'pre-Whitwick' phase: Blackbrook Reservoir Formation Ives Head Formation		BLACKBROOK GROUP

Notes:
F. = Formation
M. = Member.

Precambrian (Neoproterozoic III) age of the Charnian arc is constrained by Ediacaran-type fossil assemblages found throughout the sequence (e.g. Boynton and Ford, 1995).

It should be noted that the Precambrian outcrop is discontinuous owing to the extent of the Triassic and Quaternary cover. Consequently, many exposures do not include important contact relationships and the various boundaries shown in Figure 1 should be regarded as interpretations based on rather meagre field evidence. Mapping problems are exacerbated by the fact that the Whitwick Complex and certain components of the Charnwood Lodge Formation are unbedded, and so provide little evidence for local structural dip. The entire Charnian sequence has been recrystallized at epizonal (mid- to high-greenschist) grades of metamorphism (Merriman and Kemp, 1997), with the synchronous development of a penetrative, subvertical cleavage. Despite this, many delicate original textures are preserved as relicts, enabling these rocks to be classified petrographically.[1]

This paper describes the principal components of the Whitwick Complex and Charnwood Lodge Formation. Several units are involved, and a brief guide to the main lithologies and their likely modes of origin is therefore provided (Table 2). Given the poor exposure of these rocks, much reliance is placed on interpretations of lithology and petrology, the aim being to assess the style of Charnian volcanism by drawing comparisons with similar lithologies from modern or geologically very young volcanic arc systems.

Lithostratigraphy and geological setting

A formal terminology for rocks in or relevant to the study area is presented in Table 1, which gives stratigraphical correlations and outline environmental information. This table highlights possible links between the Whitwick Volcanic Complex and Charnwood Lodge Volcanic Formation by emphasising the occurrence of two genetic associations, representing lithologies that may have had a common origin from the same episode of magma emplacement. Investigation of these magmatic linkages is one of the major themes of this account.

The Whitwick Volcanic Complex (Moseley and Ford, 1985) is here restricted to include the non-stratiform andesites and dacites that do not form part of the Maplewell Group. It consists of massive and brecciated igneous rocks that are in part faulted against various units of the Charnwood Lodge Volcanic Formation. The component lithologies (Table 1) are termed: Peldar Dacite Breccia, Grimley Andesite and Sharpley Porphyritic Dacite, after the earlier names for the 'porphyroids' of this region (Watts, 1947; Hill and Bonney, 1891). The type locality is designated as Whitwick Quarry (445158; all grid references belong to the 'SK' square), in which all of the three units are exposed (Carney, 1994; fig. 10). 'Grimley' and 'Peldar'-type rocks also occur 3.5 km farther south, where they constitute the Bardon Hill Volcanic Complex (Carney, 1999; Carney and Pharaoh, 2000). In reality. The Bardon and Whitwick complexes may have belonged to the same magmatic feeder zone, their present geographical separation being due to subsequent faulting. The Whitwick Complex is clearly not bedded, but an overall tabular geometry is suggested for the unit by the fact that it broadly follows the 'envelope' of outcrops that continues the

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[1] Thin sections (E numbers) were cut from samples collected during the 1993-1996 re-survey of the Loughborough geological map (sheet 141), and may be examined at BGS at Keyworth.

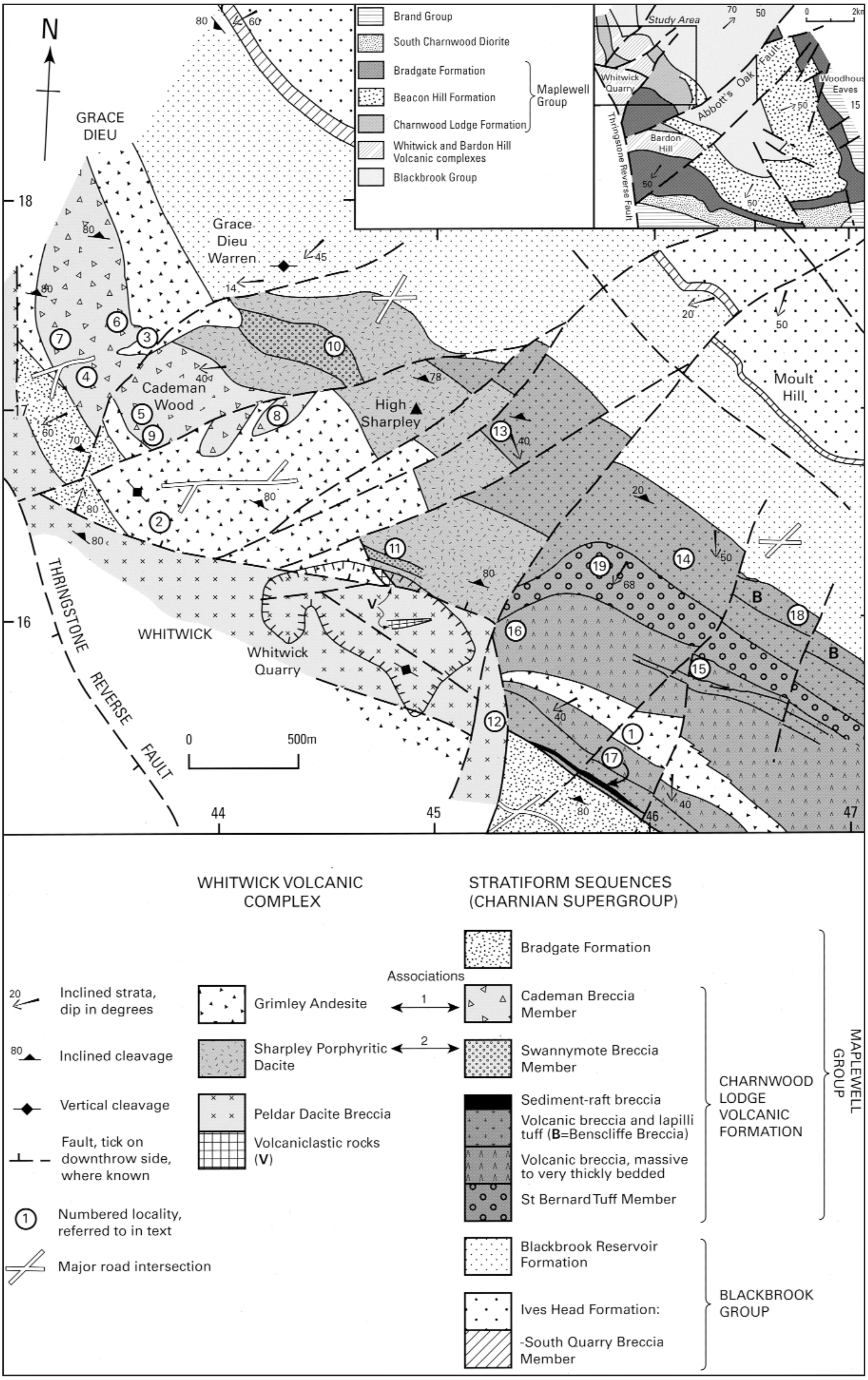

Figure 1. Geological sketch map showing the distribution of the Precambrian rocks in north-west Charnwood Forest. Triassic strata and Quaternary drift deposits are omitted, but cover about 70% of this area. The inset shows the position of the study area in relation to the main outcrop of the Charnian Supergroup and Brand Group. This area is included in O.S. Sheet 129, and in BGS Sheets 141 (Loughborough) and 155 (Coalville), at 1: 50 000 scale. For explanation of Associations land 2, see caption to Table 1.

Maplewell Group along strike to the southeast (Fig. 1, inset). Some of its components are fault-bounded, with many offsets occurring along east to northeast trending fault systems, as also featured by Bennett *et al.* (1928, fig. 21).

The Charnwood Lodge Volcanic Formation is named after the 'Charnwood Lodge Member' of Moseley and Ford (1985); formational status is now favoured because this 900-1000 m thick sequence can be further subdivided into the members shown in Table 1. It is defined as the succession of thickly stratified to massive, coarse tuffs, lapilli-tuffs and volcanic breccias that crop out in northwest Charnwood Forest, over the Blackbrook Reservoir Formation (Blackbrook Group) and in turn overlain by the Bradgate Formation which is the youngest Maplewell Group component. Moseley and Ford (1985) designated a type section for this unit in the Charnwood Lodge Nature Reserve, between Flat Hill (465161) and Warren Hills (461148), although because of the sporadic exposure it is better to regard this as a type area. A south-westerly regional dip of between 40 and 50o is assumed, from what little bedding is seen in the Charnwood Lodge and adjacent formations, and from the structural position of this area on the south-western flank of the main Charnian anticline (Fig. 1).

Magmatic feeders and extrusive products

This section investigates the basis for two major lithological associations, indicated in Table 1, that together link the activity of the Whitwick Complex to the genesis of certain rocks in the Charnwood Lodge Volcanic Formation. The object is to establish a model explaining the overall character of Charnian volcanism, and in particular the relative contributions made by the different magma sources during accumulation of the flanking volcaniclastic sequences.

The Grimley / Cademan Association

This association is defined by sparsely to moderately porphyritic lithologies that encompass high-silica andesite to low-silica dacite compositions (Fig. 9a). An igneous component is represented by the Grimley Andesite, whereas the Cademan Volcanic Breccia is interpreted (below) as a complementary, extrusive pyroclastic rock with fragments derived from the Grimley Andesite.

Grimley Andesite forms a bifurcating, northwest trending body with an estimated thickness of about 940 m. The various scattered outcrops suggest that it narrows to the south-east, and is last seen in the crags to the east of High Tor Farm (Locality 1, Fig. 1). The type area is between Whitwick Quarry (447162), the crags around Cademan Street in Whitwick village (437164), and the disused quarry at Grimley Rock (434169). The only evidence for the unit's relative age within the Whitwick Complex is provided by an exposure on the south-western face of Whitwick Quarry. This shows a dyke of Grimley Andesite, about 20 m wide, with a subvertical, chilled contact against Peldar Dacite Breccia, which it must therefore pre-date.

Lithology. Exposures of Grimley Andesite show that it is a grey-green, sparsely to moderately porphyritic lithology (Table 3). Chemically analysed samples have silica contents between 56 and 65%, with basaltic andesite, andesite and low-silica dacite compositions all represented (Fig. 9a). Although the Grimley Andesite appears to be structureless, fresh surfaces commonly reveal a shadowy breccia texture, which is a highly significant feature of the lithology. Some of the most accessible examples of this brecciated facies occur in Whitwick village, on crags overlooking the garage yard on the western side of Cademan Street (Loc. 2). There, a northerly-trending contact, which is unexposed but probably is a fault, brings in the brecciated facies on the smooth rock surfaces that form the eastern part of the exposure. The breccia features abundant, closely-packed fragments that measure up to 0.2 m across. All of these fragments consist of the same type of fine-grained andesite. They are highly angular, with lozenge or rectangular shapes (Fig. 2a). The larger of the fragments commonly show internal orthogonal joints that are filled by a fine-grained, green-grey crystalline material, which also occupies the larger areas of matrix between individual fragments. Many fragment margins can be fitted together, producing a jigsaw-type of breccia structure (Fig. 2b). In places this texture is developed on a very fine scale (Fig. 3a) and can only be detected on freshly hammered surfaces.

Grimley Andesite exposed at Hob's Hole (Loc. 3) has a heterogeneous, mottled appearance, which is not caused by brecciation but is due to the presence of abundant angular to wispy inclusions of dark green-grey andesite set in a pale grey to cream matrix. In thin section (Fig. 2c), the green-grey andesite inclusions have aphanitic or spherulitic textures and their dark colour is due to chlorite and epidote. The abundance of these minerals indicates that the inclusions are more mafic in composition than typical Grimley Andesite, which here is represented by the surrounding leucocratic, microcrystalline andesite or dacite.

Petrography. Most Grimley Andesite lithologies compare with the sample from Grimley Rock, illustrated in Figure 3b. This has microcrystalline to cryptocrystalline textures dominated by interlocking, commonly polygonal, quartzo-feldspathic aggregates. The andesite or dacite fragments in the brecciated facies of the Grimley Andesite also have this texture. The matrix between these fragments is of a coarser grain size (Fig. 3a), however, and in many samples of brecciated andesite it includes well-crystallized aggregates of chlorite and epidote, suggestive of hydrothermal or metamorphic types of mineral assemblage. Intergranular textures occur less commonly in the Grimley Andesite, an example being a fragment from the brecciated andesite facies in Whitwick Quarry in which groundmass plagioclase laths show fluxional alignment and are interspersed with Fe-Ti oxide granules and secondary white mica/chlorite aggregates (Fig. 3c).

Cademan Volcanic Breccia Member is about 450 m thick in its type area, between High Cademan

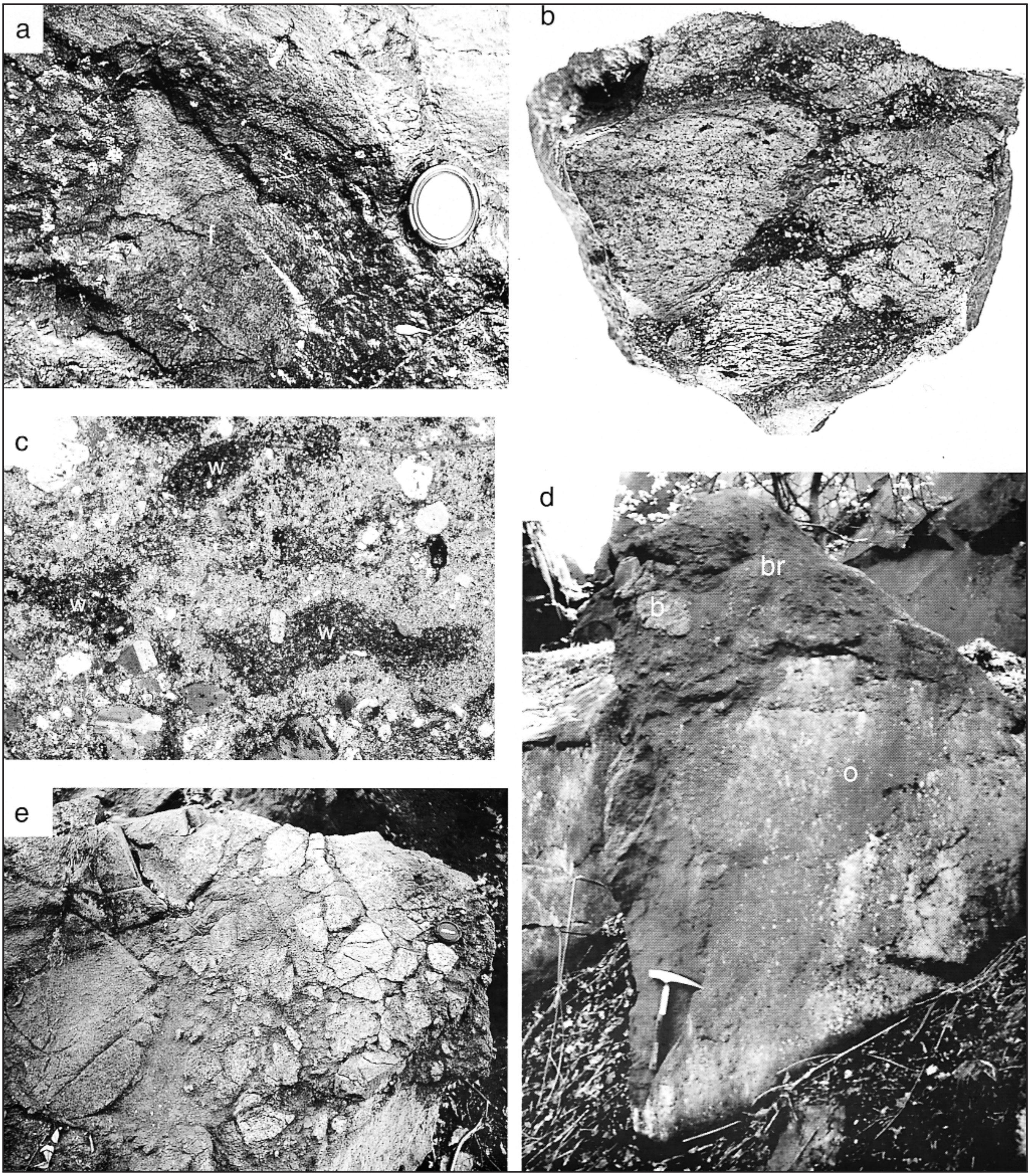

Figure 2. Lithologies of the Grimley Andesite and the Cademan Volcanic Breccia Member.
a. Exposure of brecciated Grimley Andesite at Cademan Street, Whitwick (437164), with the outline of a discrete, highly angular andesite fragment (f).
b. Slabbed specimen (JNC569), about 80 mm wide, representing part of Figure 2a and showing closely packed andesite fragments with jigsaw fit.
c. Photomicrograph (E67538) of heterogeneous Grimley Andesite from Hob's Hole (436174); the dark grey, angular to wispy areas (w) represent aphanitic, chlorite-rich fragments of ?basaltic andesite separated by more leucocratic, microcrystalline andesite or dacite. Field of view is about 5 mm wide.
d. Exposure of Cademan Volcanic Breccia at Calvary Rock (434172); the smooth rock faces represent an outsized dacite block (o), to right of hammer, surrounded by the lapilli-grade breccia matrix (br) enclosing a smaller dacite block (b).
e. Exposure of Cademan Volcanic Breccia in Grace Dieu Wood (435175). To the right of the photo, highly angular dacite blocks occur in clusters that show jigsaw fit.

(442169) and the northern end of Grace Dieu Wood (434176). These rocks were included by Watts (1947) within his `Bomb-rocks' category, and mapped as part of the Whitwick Complex by Moseley and Ford (1985). The Cademan Breccia has been distinguished here (Table 1), because it differs in two respects from the breccias that are thickly interbedded in the undivided part of the Charnwood Lodge Formation (see below). Firstly, the Cademan Breccia does not appear to be interbedded with other pyroclastic lithologies, and secondly, it generally occurs in close proximity to the main mass of the Grimley Andesite (Fig. 1). The blocks in the Cademan Breccia are of a similar lithology to the non-brecciated parts of the Grimley Andesite, and are also chemically similar, although slightly more silica-rich, plotting in the low-silica dacite field of Figure 9a. Despite these similarities, and the close field association between the two units, no clear contacts between the Cademan Breccia and Grimley Andesite are exposed.

Lithology. The spectacular monomictic breccias at Calvary Rock (Loc. 4) show most of the lithological features summarised in Table 3. They contain abundant clasts, commonly of block size (in excess of 64 mm), with rectangular to subspherical shapes, the margins of which vary from being subrounded to highly angular. It is common to see both rounded-off and angular corners in the same individual clast. The block-size clasts typically stand proud on weathered surfaces, unlike the fragments in the brecciated facies of the Grimley Andesite. They are 0.7 m across on average, but some exposures feature very large blocks, over 2 m across (Fig. 2d). The matrix to these breccias is very coarse-grained to lapilli-grade (1-64 mm size clasts), and is poorly sorted with abundant lithic fragments and crystals. Variations in the ratio of matrix to clast constituents are seen at Calvary Rock, and also near Broad Hill (Loc. 5), where the matrix locally occupies 50-70% of some breccias. These matrix-rich rocks remain poorly sorted, with larger clasts scattered about, but the latter are relatively small in size (up to several centimetres across) when compared to blocks in the more typical Cademan Breccia lithology. A distinctive variant of breccia occurs in Grace Dieu Wood, north-west of Hob's Hole (Loc. 6). It features well-jointed and highly angular blocks of the usual fine-grained, sparsely porphyritic dacite, some so close to each other that their outlines have a jigsaw fit (Fig. 2e). Between these blocks is a poorly sorted, mainly lapilli-grade matrix consisting of lithic fragments and euhedral or fragmented plagioclase crystals. Farther north, and west (Loc. 7), in Grace Dieu Wood, there are breccias in which the andesite blocks have cream to pale pink colours, in marked contrast to the coarse-grained, grey-green breccia matrix.

High Cademan is the only area where outcrops of the Cademan Volcanic Breccia and Grimley Andesite are observed close together. On the eastern flank of High Cademan (Loc. 8, 442169) most exposures show the rough rock surfaces and large blocks typical of the Cademan Volcanic Breccia. This breccia texture disappears westwards, however, and the summit of High Cademan is occupied by a massive, smooth-surfaced lithology equated with Grimley Andesite. The contact between the two is hidden, but immediately east some outcrops show metre-scale alternations, apparently between Cademan Breccia and relatively more massive Grimley Andesite. This layering dips about 55o to NE 020, but an original vertical attitude results if a correction is made for the presumed 40-50o south-westward regional dip. Cademan Volcanic Breccia exposed farther north (439171) shows prominent planar surfaces that are inclined south-westwards, in the inferred regional dip direction. A rare exposure of a contact occurs by the footpath down the western flank of Temple Hill (Loc. 9), where volcanic breccia rests on a 50 mm-thick, dark grey, fine-grained fragmental layer. The latter is unique amongst the rocks sampled to date, in that it is composed of slivers or irregular masses of glassy volcanic rock showing well preserved perlitic texture (Fig. 3d). The layer is underlain by a grey, feldspar-rich andesite, suggesting that the glassy lithology may represent part of the latter's brecciated chilled margin.

Petrography. Dacite blocks in the Cademan Volcanic Breccia have predominantly microcrystalline to cryptocrystalline textures. At the Calvary Rock exposures, phenocrysts are small and include sporadic quartz and up to 30% of heavily altered euhedral plagioclase; these blocks also contain prismatic chloritic pseudomorphs after original hornblende. A thin section of a breccia block from west of Grace Dieu Wood (Loc. 7) features a microcrystalline groundmass that is typical of these lithologies. This sample shows textural heterogeneity, which is imparted by abundant rounded, elliptical or veinlet-like segregations of better-crystallized quartzo-feldspathic material (Fig. 3e). In the same thin section there are domains that preserve shadowy, circular, microcrystalline areas reminiscent of a recrystallized spherulitic or micropoikilitic texture. Thin sections of the the jigsaw breccias described at Loc. 6 show that in the matrix between the blocks, lithic fragments locally predominate over plagioclase crystals. These lithic grains range from fine-ash to lapilli size and although they mostly have microcrystalline to cryptocrystalline textures, one lapilli-size clast (15 mm across) is of finely equigranular quartz microdiorite (Fig. 3f).

Interpretation of Grimley/Cademan Association:

In the Cademan Breccia Member, the abundance of blocks suggests deposition by gravity processes operating in an environment of steep slopes. Angular corners indicate that many blocks experienced minimal abrasion, with those that are more rounded testifying to abrasion produced by clast collisions during transport. Metres-size blocks, some with jigsaw textures, indicate in situ fragmentation prior to consolidation of the deposit. The monomictic nature of the Cademan Breccia, and the fact that its clasts are closely similar in appearance and petrography to the Grimley Andesite (compare Figs. 3a&b with 3e&f) are features suggesting a genetic link between the two. For example, the Grimley Andesite may be a lava flow with the Cademan Breccia as the autobrecciated part of the lava. Alternatively, the Grimley Andesite could have been extruded as volcanic domes, with the Cademan Breccia representing their brecciated margins and talus and/or the deposits of block and ash pyroclastic flows that originated from the disintegration and collapse of the domes as recently witnessed on Montserrat (Young *et al*., 1998).

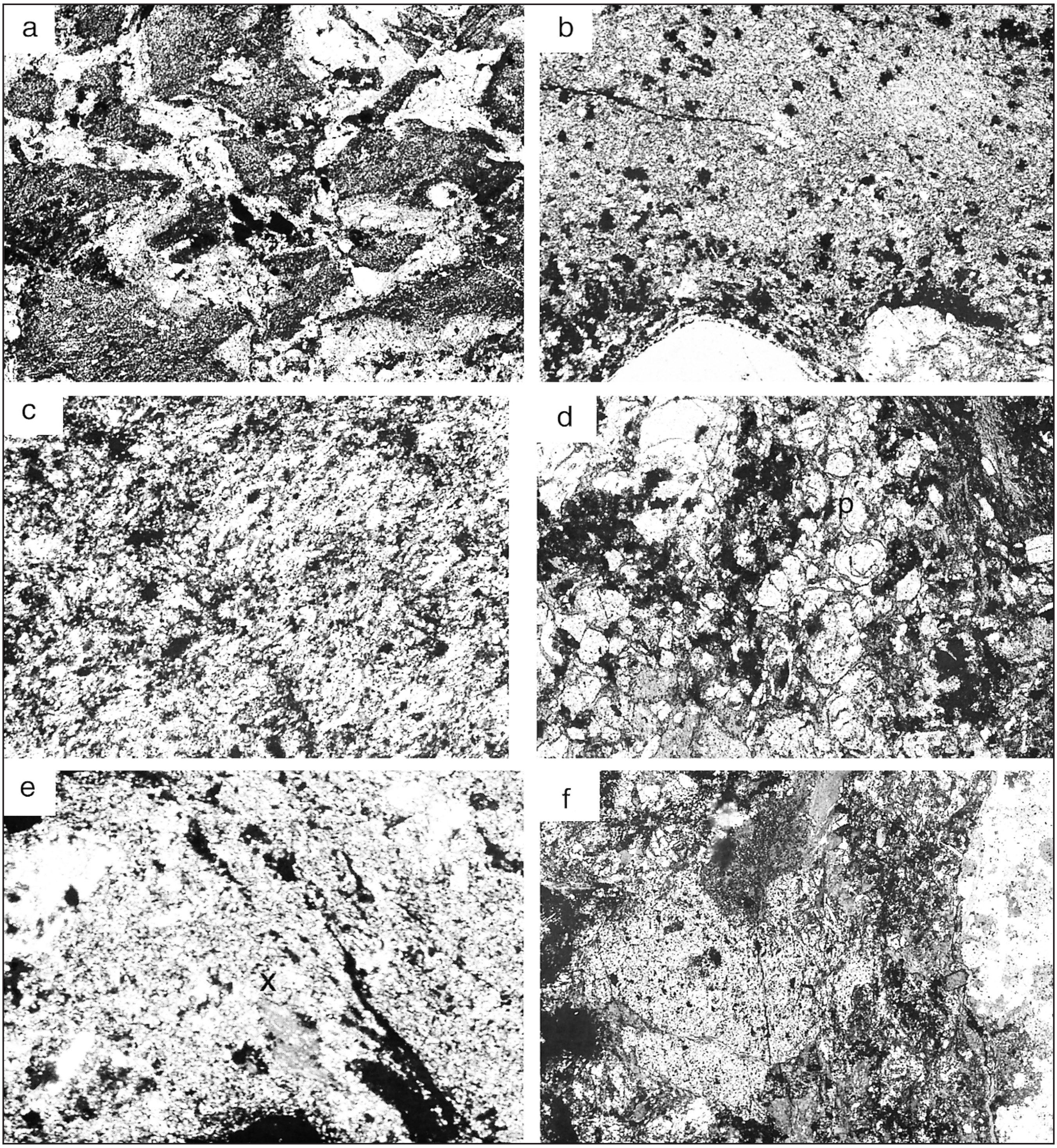

Figure 3. Photomicrographs of rocks from the Grimley/ Cademan association.

a. Grimley Andesite microbreccia (E67539) south-east of Hob's Hole (437174), with angular fragments of cryptocrystalline andesite (dark grey areas) in a coarser leucocratic microcrystalline matrix; field of view is 5 mm wide.

b. Grimley Andesite sample (E67535) from Grimley Rock (434169) showing microcrystalline to cryptocrystalline groundmass texture and magmatically corroded quartz phenocryst (at lower left); field of view is about 5 mm wide.

c. Grimley Andesite (E67549) from Whitwick Quarry, showing intergranular texture and fluxional alignment of plagioclase laths; field of view is about 7 mm wide.

d. Possible chilled margin (E67532) from a contact between andesite and ?Cademan Volcanic Breccia on western flank of Temple Hill (437168). Circular areas of recrystallized perlitic volcanic glass are seen below 'p'; the field of view is 3 mm wide.

e. Dacite block (E67543) from the Cademan Volcanic Breccia in western Grace Dieu Wood (432173). A microcrystalline to cryptocrystalline groundmass has diffuse quartz-rich areas (just right of 'x'); field of view is 2 mm wide.

f. Matrix to the Cademan Volcanic Breccia (E67542) from the locality shown in Figure 2e. The fragments include equigranular quartz-microdiorite, at right-hand margin of photo, but more commonly are of ragged-margined cryptocrystalline dacite (cp); field of view is 3 mm wide.

Because of poor exposure, contact relationships are not sufficiently clear to differentiate between these hypotheses. However, apart from in the High Cademan area, the lack of intercalation of the two units does not support the idea that the Cademan Breccia represents an autobreccia of Grimley Andesite lavas. On the other hand, the textures of the Cademan blocks are generally cryptocrystalline or microcrystalline, albeit with some variation in the degree of crystallinity. They are similar to the many examples given by Murphy and Marsh (1993) of 'dense', non-vesicular and non-glassy material produced by repeated recrystallization within relatively slowly emplaced subvolcanic to extrusive domes or vent-filling dome plugs. The preferred interpretation is that the Grimley Andesite was emplaced in intrusive/extrusive domes, and the Cademan Breccia represents the brecciated margin or talus apron of the domes or, as suggested in Figure 10, block and ash pyroclastic flows generated by the collapse and disintegration of the domes. Such flows, once initiated, would travel down the sides of the volcanic edifices essentially as debris avalanches. Examples of the latter from the volcaniclastic apron of Ruapehu volcano in New Zealand show jigsaw-type clasts (McPhie *et al.*, 1993, plate 36.3) similar to parts of the Cademan Breccia.

Internal brecciation is an integral feature of the Grimley Andesite, and may have occurred in the late syn-volcanic environment, where processes such as autobrecciation or hydraulic fracturing (Cas and Wright, 1987) would be expected to operate during inflation of a consolidated extrusive andesite dome. The well-documented 1995-1997 eruptive phase of Montserrat offers a possible modern analogue for this type of deformation, which may be associated with the generation of the 'hybrid earthquake' swarms that were detected at shallow depths immediately beneath the active crater into which the domes were rising (Miller *et al.*, 1998). These earthquakes were attributed to multiple hydrofracturing events during the build up of conduit gas pressure (Voight *et al.*, 1999).

The heterogeneous sample of Grimley Andesite shown in Figure 2c may suggest that mixing has occurred between magmas of contrasting composition. This should be established by chemical analysis of the mafic inclusions, but if confirmed it would be an important observation, since magma mixing may have been involved in triggering eruptions at Montserrat (Murphy *et al.*, 1998).

A subaerial environment for the Grimley dome extrusion in Association 1 is suggested by the general lack of evidence for interaction with water or water-saturated sediment. In the absence of criteria such as sedimentary structures in fine-grained facies, this must remain a speculative conclusion. Subaqueous deposition of the Cademan Breccia is nevertheless a possibility, by analogy with the volcanism of Montserrat, where block and ash pyroclastic flows originating from sequential dome collapses have formed a fan complex that has prograded into the surrounding sea (Cole et al., 1998). The great thickness of the Cademan Breccia militates against it being a single block and ash pyroclastic flow, but could suggest an origin as a series of amalgamated flows deposited on a subaqueous fan (Fig. 10). Variations in the proportions of matrix and clasts in the Cademan Breccia suggest that it may have a degree of stratification in keeping with an amalgamated flow origin. The accumulation of thick pyroclastic sequences would be favoured by 'ponding' of the various flows, perhaps against the wall of a caldera that contained the rising domes. It would be expected from this that block and ash pyroclastic flows would be thickest at their final resting site, some distance away from their point of origin. This is clearly not in keeping with the close field association seen here between the Grimley Andesite and very thickly developed Cademan Breccia. If this region experienced a long history of multiple dome activity, however, the present Grimley Andesite could represent the root zones of younger magmatic domes that had risen through pre-existing volcaniclastic accumulations that included the Cademan Breccia (Fig. 10).

The Sharpley / Swannymote Association

This association is defined by highly porphyritic (plagioclase-quartz) lithologies that in chemical terms encompass dacitic and rhyolitic compositions (Fig. 9a). The Sharpley Porphyritic Dacite represents a possible shallow-level intrusive igneous rock, whereas the Swannymote Volcanic Breccia Member may be a complementary breccia component (e.g. Table 3) containung fragments from the Sharpley Dacite.

Sharpley Porphyritic Dacite is massive and homo-geneous, with 40-50% of phenocrysts represented by large (up to 10 mm) white plagioclase feldspar and subordinate but equally large, rounded, green-grey quartz (Table 2). The fine-grained groundmass has a grey to lavender colour on fresh surfaces, becoming pale grey when weathered. Silica contents are 70-72%, suggesting a dacitic to rhyolitic composition (Fig. 9a); however, the possible mobilisation of silica in the post-magmatic, metamorphic environment is a constraint on rock classifications based solely on chemical compositions. The principal exposures and the type locality are around High Sharpley (448171), and the unit maps out (Fig. 1) as a fault-segmented northwest trending body that may be up to 600 m thick in places.

The most obvious primary structure of the High Sharpley exposures consists of prominent planar surfaces inclined towards the southwest, parallel to the inferred regional dip. Viewed in plan, these surfaces display systems of rectangular to polygonal-

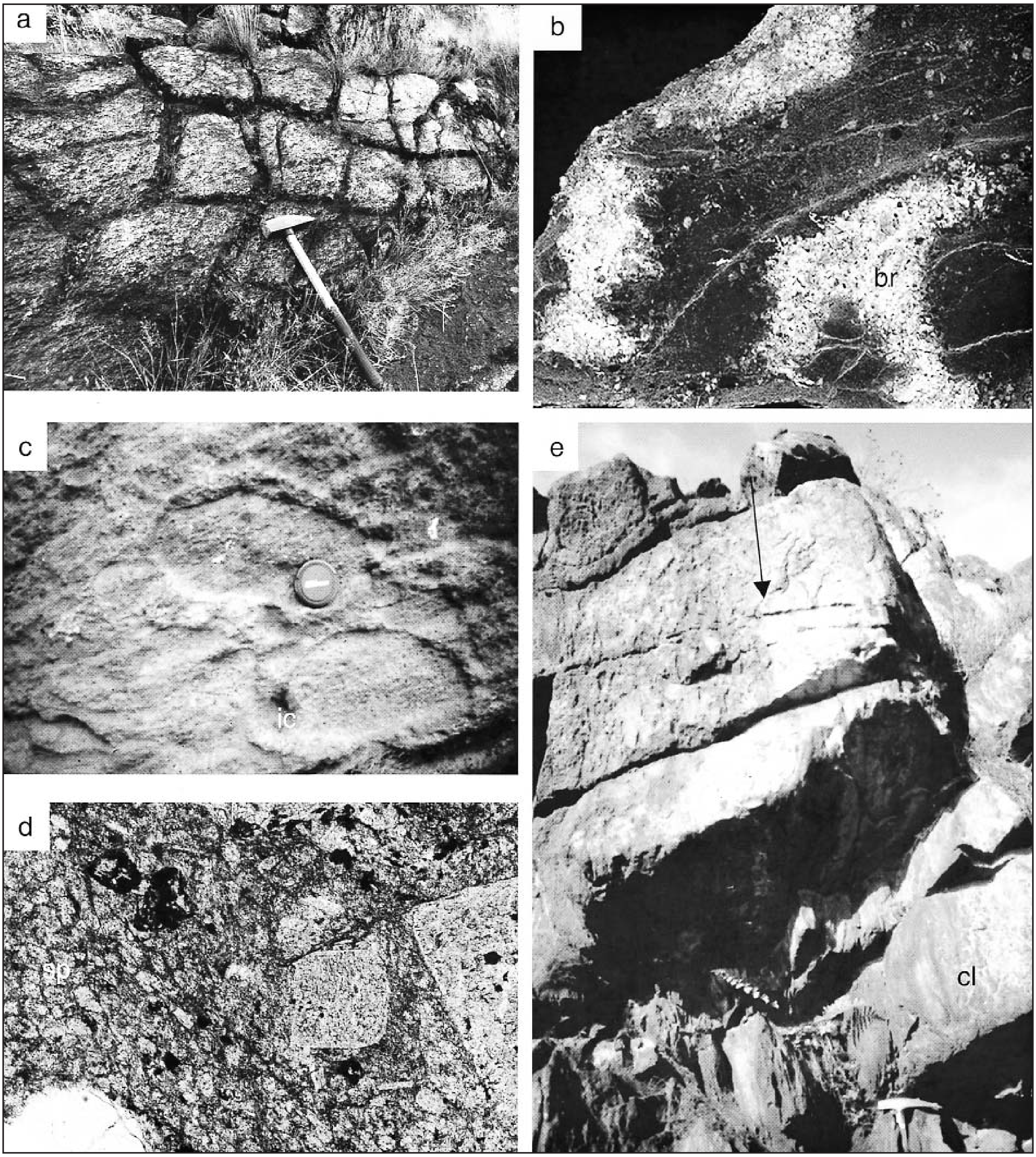

Figure 4. Lithologies of the Sharpley Porphyritic Dacite and the Swannymote Breccia Member.
a. Sharpley Porphyritic Dacite exposed on High Sharpley (448171), with polygonal jointing pattern.
b. Slabbed specimen of Swannymote Breccia (JNC 501) from an exposure to the west of Swannymote Rock (445172); complex intermixing has occurred between the crystal-rich breccia matrix (br) and darker-toned volcaniclastic siltstone. The slab is about 50 mm wide.
c. Typical appearance of the Swannymote Breccia on Ratchet Hill (447163); the block-size porphyritic volcanic fragments have rounded to possibly incurved margins (eg. just above 'ic').
d. Photomicrograph of Swannymote Breccia (E67524) from Ratchet Hill (447163), showing an enlarged area of a lapilli-size volcanic fragment with spherulitic texture (sp); the field of view is 2 mm wide.
e. Near Ratchet Hill summit (447163), the eastern junction (arrowed) of the Swannymote Breccia (rough-textured lithology) with the Sharpley Porphyritic Dacite seen to the right (northeast). The dacite has a diffusely fragmental texture, with a possible ovoid clast occurring to the left of 'cl'.

shaped joints spaced at between 0.5 and 1 m (Fig. 4a). The joints continue into the rock for at least 2 m, dividing it into narrow, oblong-shaped domains in side-section; the structure is not related to the Charnian cleavage, and resembles deformed columnar joints.

Thin sections of fresh samples of Sharpley Dacite from Whitwick Quarry have homogeneous groundmasses consisting of a microcrystalline quartzo-feldspathic base interspersed with secondary laths of colourless mica (Fig. 5a). Stringers of leucoxenised mafic material anastomose across the groundmass.

Contact relationships along the western margin of the Sharpley Porphyritic Dacite are exposed on the north face of Whitwick Quarry, immediately below Ratchet Hill. Here, the unit adjoins a 28 m-thick volcaniclastic succession ('v' in Fig. 1), which is subvertical and tectonically sheared. About one centimetre from the volcaniclastic rocks, phenocrysts become smaller and more scattered, and small flames and rafts of purplish grey siltstone occur within the otherwise intact Sharpley Dacite. The contact zone of the dacite is probably gradational for a further 12 m into the adjoining volcaniclastic succession since the latter includes at least four thin screens of 'Sharpley'-type porphyritic dacite and dacitic volcanic breccia. The sedimentary rocks mainly consist of crystal-rich volcaniclastic sandstones and siltstones. They show contortion and slump-folding of laminae and, despite the strong deformation, graded bedding can be seen, which indicates that the sequence `youngs' to the west, away from the Sharpley Dacite. Natural exposures of a further contact, between the Swannymote Breccia and Sharpley Dacite, occur on the nearby Ratchet Hill and are described below.

Swannymote Breccia Member was named after its type area around Swannymote Rock (Loc. 10), the only other occurrence being at Ratchet Hill (Loc. 11). It may be up to 200 m thick, but this must be regarded as a tentative estimate since it is seldom exposed. The Swannymote Breccia has a close spatial relationship with outcrops of the Sharpley Porphyritic Dacite (Fig. 1), particularly between Ratchet Hill and Whitwick Quarry. It resembles the Cademan Breccia in that it is predominantly composed of unbedded volcanic breccia, but the blocks found in these rocks are different in that they are highly porphyritic, with large phenocrysts of white plagioclase and rounded, grey-green quartz (Table 3). The Swannymote blocks instead resemble typical Sharpley Porphyritic Dacite in their gross lithology, although not always in detail since some have darker grey groundmasses. The phenocrysts of the breccia blocks are also slightly smaller than those in the Sharpley Porphyritic Dacite; they average about 2 mm but are locally up to 5 mm in size. Chemical analyses (see below) indicate that the Swannymote blocks have generally higher silica contents than the Sharpley Porphyritic Dacite. Their compositions are appropriate to rhyolite (Fig. 9a), but as discussed below this may in part reflect modification resulting from element mobility in the post-magmatic environment.

Lithology. The northeastern part of Swannymote Rock exposes massive volcanic breccia with abundant (c.50-60%) porphyritic rhyolite blocks, up to 1 m across, which are subrounded with elliptical to rectangular sections. The coarse-grained to lapilli-size breccia matrix contains closely packed plagioclase and quartz crystals. Southwest of the knoll, the breccia matrix becomes extensively admixed with very fine-grained, grey, faintly laminated volcaniclastic siltstone. A polished slab of this lithology (Fig. 4b) shows wispy lenticles and `floating' crystal-rich aggregates representing elements of the breccia matrix dispersed within the siltstone. Thin sections of this disrupted part of the breccia show very fine-grained lithic fragments with pervasive spherulitic textures, similar to those illustrated in Figure 4d. About 20 m farther southwest, exposures show breccia crammed with small (2-3 cm size) porphyritic clasts, some with strongly arcuate to incurved and cuspate outlines.

Field relationships at Ratchet Hill (Loc. 11) indicate that the Swannymote Breccia Member forms a screen that is wholly enclosed within the Sharpley Porphyritic Dacite. Here, it is a poorly sorted lithology composed of subspherical to elliptical porphyritic rhyolite blocks, up to 0.4 m in size, with subrounded or well-rounded margins (Fig. 4c); these blocks are typically recessed-in to the matrix due to differential weathering. The northeastern junction of this breccia is exposed 70 m west of the summit of Ratchet Hill, appearing as a sharp interface when viewed end-on (Fig. 4e). Close inspection shows that the adjacent Sharpley Porphyritic Dacite has a diffusely fragmental appearance, with ovoid-shaped enclaves that have not been observed elsewhere in this unit. This fragmental facies fades over about 100 m to the northeast, away from the contact shown in Figure 4e and towards exposures in the massive Sharpley lithology.

On the southern part of Ratchet Hill, the volcanic breccias contain rafts of grey, laminated siltstone. This recalls the situation at Swannymote Rock, except that there is no obvious breccia/soft-sediment intermixing and the lamination within the siltstone rafts is sharply truncated by the matrix of the breccia.

Petrography. Thin sections show that the blocks in the Swannymote Breccia contain common phenocrysts of wholly or partly disaggregated plagioclase and rounded, marginally embayed quartz. A typical breccia block from Ratchet Hill has a groundmass composed of microcrystalline quartzo-feldspathic aggregates interspersed with plagioclase microlites (Fig. 5b). A very coarse-grained and poorly sorted matrix intervenes between individual blocks of the breccia; this matrix consists of granulated crystals concentrated between abundant, ash- to fine-lapilli size (1-3 mm) fragments of microcrystalline dacite (Fig. 5c), some with relict spherulitic textures (Fig. 4d).

Interpretation of the Sharpley/Swannymote Association: In part, the Swannymote Breccia resembles the coarsely fragmental rocks of the Cademan Breccia Member, but relationships of the type seen at Swannymote Rock show that there was

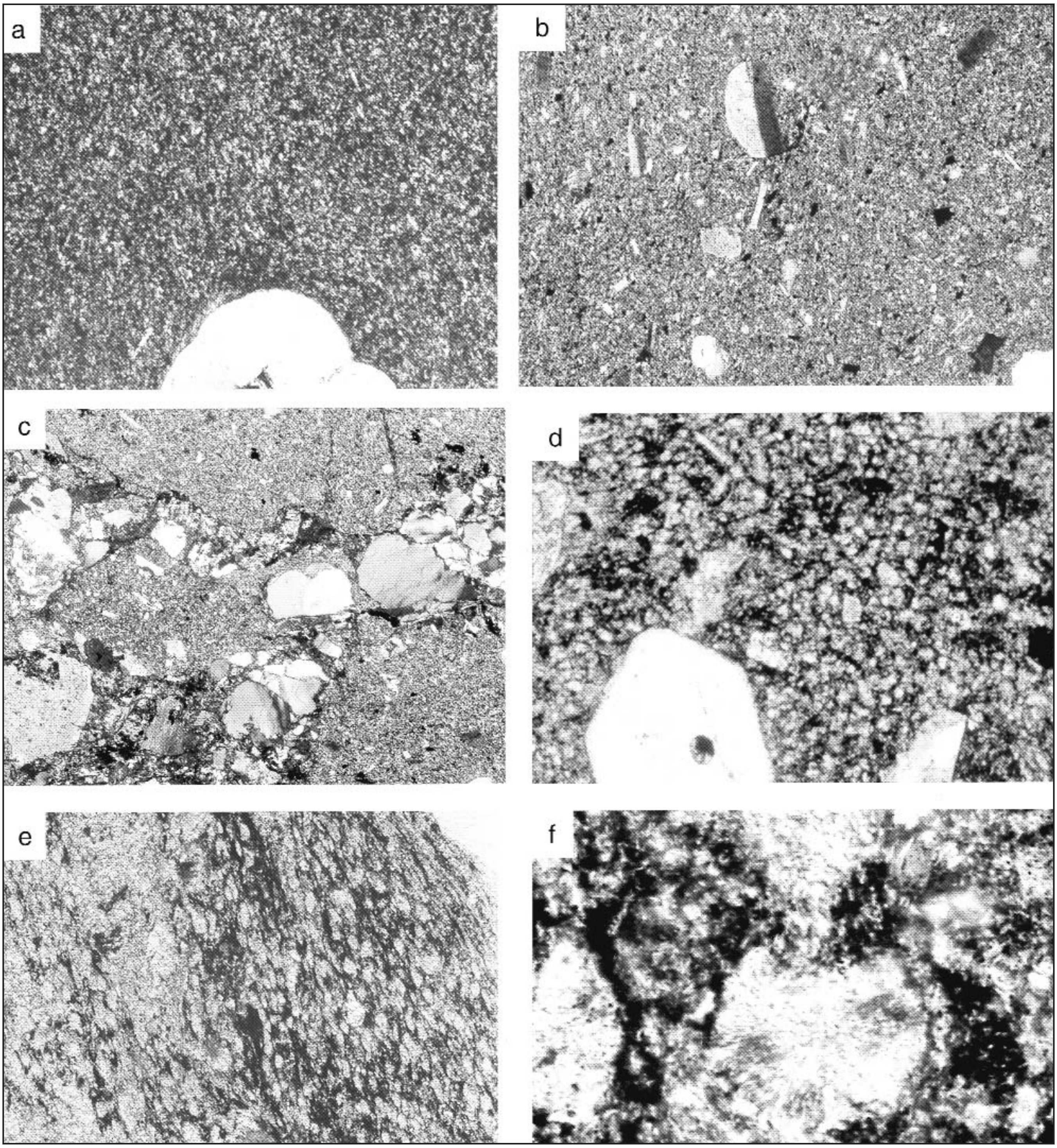

Figure 5. Photomicrographs of the Sharpley, Swannymote and Peldar rocks.
a. Sharpley Porphyritic Dacite (E67678), showing microcrystalline groundmass and rounded quartz phenocryst at lower margin; the field of view is about 2 mm wide.
b. Porphyritic volcanic block (E67523) from the Swannymote Breccia at Ratchet Hill (447163), showing microcrystalline groundmass texture and plagioclase microphenocrysts; the field of view is about 2.5 mm wide.
c. Matrix of Swannymote Breccia (E67524; see also, Fig. 4d) showing microcrystalline to cryptocrystalline-textured lithic clasts with intervening areas rich in granulated quartz and plagioclase crystals; field of view is 4.5 mm wide.
d. Textures in a cognate fragment of porphyritic dacite (E67547A) in Peldar Dacite Breccia from Whitwick Quarry (see Fig. 6a), showing oxides-rich groundmass in which quartzofeldspathic areas (pale grey) form microgranular clumps; a euhedral quartz microphenocryst is seen at lower photo margin. Field of view is about 1.3 mm wide.
e. Matrix of Peldar Dacite Breccia (E67476) from Whitwick Quarry, showing globulose 'micro-spherulitic' texture, which is an accentuation of that seen in Figure 5d. The attenuation of the spherulites is a superimposed effect caused by later deformation; field of view is about 3 mm wide.
f. Enlargement of an undeformed spherulite from image 'e'. Note the fibrous, radiating arrangement of quartz and feldspar crystallites and 'bow-tie' extinction; field of view is 0.7 mm wide.

interaction between the breccia and unconsolidated, water-saturated sediments. An important aspect of these mixing phenomena is their association with the development of spherulitic textures in some of the breccia fragments. Spherulites have commonly been attributed to the devitrification of volcanic glass, and Lofgren (1971) has demonstrated that their development would be favoured in magmas that had cooled to glass but were then subjected to slow, solid-state crystallization at sustained elevated temperatures in the presence of circulating fluids. McArthur *et al* (1998) further suggest that spherulites can nucleate above the glass transition temperature, during the cooling of magmas emplaced at shallow levels. Spherulites can form in a wide range of environments, including subaerial conditions, but, in the context of the field relations seen here, they could be attributed to the relatively slow cooling of magmas intruded into, and insulated by, a carapace of wet sediment. An interpretation of parts of this unit as peperitic breccias (formed by the disintegration of magma in contact with wet sediments) may also explain the rounded to incurved outlines of certain of the blocks at Swannymote Rock, indicative of pillow formation. The relationships seen near Ratchet Hill are of a different type, featuring sharp margins between breccia and rafted sedimentary clasts. They suggest that. at least locally, the host sediments were consolidated prior to their incorporation into the breccia.

The Sharpley Porphyritic Dacite constitutes the obvious source of porphyritic blocks in the Swannymote Breccia, but its precise mode of origin is uncertain. Except for its fragmental marginal contact zone with the Swannymote Breccia, and with the volcaniclastic rocks in Whitwick Quarry, it is a homogeneous body. A possible tabular geometry is indicated by the bedding-parallel internal planar structure of the dacite, and its columnar jointing further suggests that these planes may be the boundaries to internal cooling units. A mode of origin as a sill or laccolith, or perhaps a cryptodome, emplaced within an unconsolidated or partly consolidated sedimentary carapace, could explain the dacite's marginally brecciated condition and its intergradational relationship with the Swannymote Breccia. A parallel may be found in the Jurassic-age volcanic arc sequences of southern Chile (Hanson and Wilson, 1993), where spherulitic textures are described in association with 'hyaloclastites', including monolithological debris flow deposits and peperites, formed where silicic magmas have cooled within an insulating carapace of wet sediments. These terranes feature largely coherent silicic bodies, which are possible analogues for the Sharpley Porphyritic Dacite.

Peldar Dacite Breccia

The most distinctive features of this unit, summarised in Table 3, are its dark grey to black appearance, abundance of large phenocrysts, and textures indicative of thorough brecciation (Fig. 6a). The name for this unit is based on the terminology of Watts (1947), who referred to these rocks as the Peldar Tor variety of `porphyroid'. The type locality is to the south of the major fault in Whitwick Quarry (Carney, 1994; fig. 10), occupying the former site of Peldar Tor. The unit is poorly exposed outside the quarry, but is interpreted as a laterally extensive body, about 520 m thick, with sharply-defined contacts that are at least in part faulted. It is relared to the less becciated porphyritic dacite ('Peldar Porphyroid' of Jones, 1926) of Bardon Quarry, farther to the south (Carney and Pharaoh, 2000). Although the best *in situ* exposures of the unit are confined to Whitwick Quarry, impressive specimens can be examined in the walls and grounds of the Mount St Bernard Monastery (458163).

In Whitwick Quarry the Peldar Dacite Breccia is juxtaposed against other components of the Whitwick Complex by a major fault. This structure consists of brecciated fault-rock tens of metres thick; a northerly downthrow (Fig. 1) is inferred from microfabric analysis of phyllonitic ductile shear zones coincident with the fault (Carney, 1994). The Peldar Dacite Breccia is typically devoid of stratification, but on the northeastern and southeastern lower levels of the quarry there are diffuse contacts between matrix-rich and matrix-poor breccia facies inclined steeply (70-50°) to the north-east; on correcting for the regional south-west dip, this would give an original subvertical orientation.

The Peldar Dacite Breccia has a heterogeneous lithology that consists of three components.

Porphyritic dacite fragments are essential, 'cognate' constituents of the Peldar Dacite Breccia. They vary in abundance, and in rare instances are not present at all, but in most exposures they comprise over 80% of the rock (averaging about 65%). The fragments range in size from about a centimetre (Fig. 6a) to over a metre, and though some are highly angular, many others have rounded to elliptical shapes as can be seen in some of the slabs set into the walls of Mount St. Bernard Monastery. Incurved embayments and cuspate promontories characterize some of the larger and more irregularly shaped masses of porphyritic dacite; they resemble pillows, except that their margins are very sharp against the breccia matrix, with no obvious signs of marginal chilled rims. The porphyritic dacite fragments have dark grey to black, fine-grained groundmasses which enclose large (3-7 mm) creamy white euhedra or glomerophyric aggregates of plagioclase (comprising about 40% of the dacite) and equally large, rounded, phenocrysts of greenish grey quartz (about 10-15%). Their groundmasses have an unusual texture, which features numerous rounded, or rosette-like, microgranular clumps of strongly zoned quartz and feldspar (Fig. 5d). In the aphanitic matrix between these quartzo-feldspathic clumps there are finely disseminated iron-titanium (Fe-Ti) oxides, their abundance probably contributing to the dark grey or black appearance of the porphyritic dacite fragments.

Quartz microdiorite fragments are medium-grained and pale green, and generally measure from a few millimetres to several centimetres in size (average about 50 mm). Most are rounded or subangular, and have discoid to subspherical or ovoid shapes. They are enclosed within both the breccia matrix and the porphyritic dacite fragments and commonly comprise a few per cent of the rock, although in some parts of breccia they are the only type of fragment that is present. In thin sections quartz microdiorite fragments consist of abundant, stubby, hypidiomorphic plagioclase crystals which are part-enclosed by quartz crystals or aggregates, some with euhedral terminations. Interstitial albite, leucoxenized oxide minerals, and secondary chlorite-epidote aggregates, are the other constituents.

The matrix of the Peldar Dacite Breccia is a dark grey, fine- to medium-grained fragmental lithology (Fig. 6a), speckled with small, granulated plagioclase and quartz crystals. It is mostly composed of oval to sliver-shaped clasts of turbid, oxides-rich aphanitic volcanic rock studded with quartzo-feldspathic micro-globules of 0.2 mm average diameter (Fig. 5e). The globules are locally attenuated into ellipses by the penetrative cleavage, but where undeformed they exhibit a fibrous, radiating crystal growth (Fig. 5f) typical of spherulitic crystallization.

Intricate contact relationships are seen at the margins of a raft-like sedimentary inclusion, just over 100 m long, which is completely enclosed within the Peldar Dacite Breccia in the central part of Whitwick Quarry (Fig. 1). The sedimentary rocks consist of maroon to purple volcaniclastic siltstone exhibiting highly contorted and slumped lamination. Their contact with the Peldar Dacite Breccia is a complex zone of mingling, with coarse-grained lenticles of the crystal-rich breccia matrix in the siltstone, and rafts and wisps of maroon siltstone enclosed within the adjacent dacite breccia matrix (Fig. 6b). On a higher quarry level, the siltstone of the rafts passes into a grey, medium- to coarse-grained volcaniclastic rock, that strongly resembles the matrix component of the Peldar Dacite Breccia.

The Peldar Dacite Breccia is not obviously part of any lithological association, comparable to the Grimley/Cademan and Sharpley/Swannymote groupings, but possible ‘extrusive’ equivalents have been identified. One significant occurrence was noted on the northern face of Whitwick Quarry, where screens of Peldar Dacite Breccia between 2 and 8 m thick are interleaved within the 28 m thick succession of volcaniclastic rocks (‘v’ in Fig. 1), described earlier, sandwiched between Grimley Andesite and Sharpley Dacite. A rather more isolated exposure, in fields south-east of Whitwick Quarry (Loc. 12), shows volcanic breccia containing abundant dark-matrix feldsparphyric blocks, up to 0.4 m across, with margins recessed-in to the matrix. Some of the smaller volcanic clasts in this rock have globulose areas that are identical to the micro-spherulitic textures described above for the Peldar Dacite Breccia matrix. Other clasts are more coarsely textured, with strikingly well developed, rosette-shaped, quartzo-feldspathic spherulites.

Interpretation: The most significant features of the Peldar Dacite Breccia are its all-pervasive fragmentation and the textural variations between the matrix and the enclosed fragments or irregular masses of porphyritic dacite. The latter are particularly abundant, and are regarded as being cognate, in the sense of representing the remnants of the dacite magma that had disintegrated to form the breccia. The groundmasses of the porphyritic dacite fragments are texturally similar to rocks that have been cooled under hydrous conditions, permitting limited crystallization to occur (e.g. Murphy and Marsh, 1993). Possibly this crystallization regime

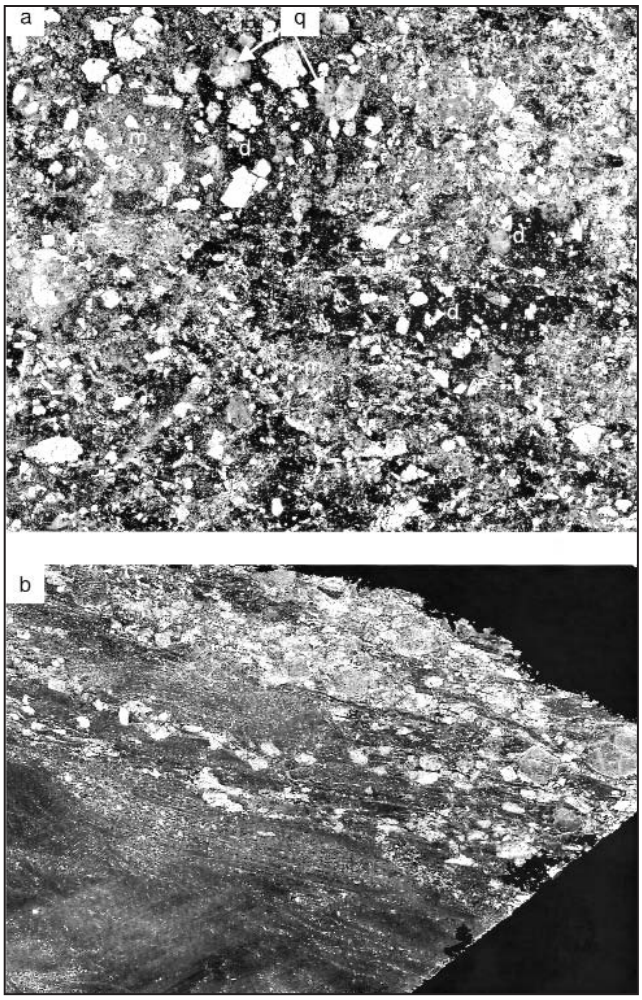

Figure 6. Lithologies of the Peldar Dacite Breccia from Whitwick Quarry.

a. Cut slab (JNC531), with contrast enhanced to show dark-toned areas representing scattered, cognate fragments of porphyritic dacite (d) with phenocrysts of euhedral plagioclase and rounded, radially fractured quartz (q). Paler-toned matrix (m) consists of spherulitic-textured dacite slivers (Fig. 5e) with smaller crystals; specimen is 95 mm wide.

b. Junction between Peldar Dacite Breccia and the raft of volcaniclastic siltstone in the centre of Whitwick Quarry (JNC550). Lenticles of crystal-rich material from the breccia are intercalated within darker-toned siltstone, the latter decreasing in abundance towards the top of the picture (closer to the main breccia mass); field of view is 80 mm wide.

resulted in the incipient development of a spherulitic texture, seen as the microgranular clumps in Figure 5d. The spherulitic textures of the small, sliver-shaped fragments that constitute the matrix of the breccia are interpreted as representing a greater extent of recrystallization within the matrix of the Pedlar Dacite Breccia compared to the textures of the porphyritic dacite fragments (compare Figs. 5d and e).

As previously noted, Lofgren (1971) has suggested that spherulites would be favoured in devitrifying volcanic glass that cooled relatively slowly, in the presence of elevated temperatures and circulating heated waters. It is therefore possible that the Peldar Dacite Breccia is comparable to certain intrusive hydroclastic breccias in submarine volcanic arc sequences in California (Hanson, 1991). Such lithologies represent large volumes of silicic magma that were subjected to complete, non-explosive in situ disintegration when they were quenched within a carapace of wet sea-floor sediments. Kokelaar (1986) has described some of the processes that may operate in such environments. In the case of the Peldar Dacite Breccia, these could include: *cooling contraction granulation*, in response to thermal stresses produced during rapid and uneven chilling, which would have shattered the dacite and its crystals, and *dynamic stressing*, which would have been exerted upon the chilled surfaces of the dacite masses by movements of the magma within the developing pillows. Acting in combination, these processes would have broken up the more rapidly cooled parts of the magma, thereby contributing the abundant spherulitic glass slivers seen in the breccia matrix. The lack of jigsaw fits between the porphyritic dacite fragments indicates that movements exerted during emplacement of the dacite largely destroyed *in situ* brecciation textures.

The margins of the sedimentary raft at Whitwick Quarry indicate that the breccia matrix and the host siltstone were both in an unconsolidated state, when disaggregation occurred; this is further support for interpretation of the Peldar Dacite Breccia as a type of peperite, or hyaloclastite breccia. Magma emplacement within a carapace of unconsolidated wet sediment would provide the insulation and also the confining pressures (see Discussion below) necessary for relatively slow cooling, permitting cryptocrystalline or spherulitic crystallization styles to develop. Magma-wet sediment interactions could also explain the angular to incurved, cuspate boundaries of the larger porphyritic dacite masses, some of which may be the kernels of original pillows. The quartz microdiorite fragments are xenoliths of a previously crystallized, hypabyssal intrusive rock, perhaps part of an earlier magma chamber through which the Peldar dacitic magmas rose. The original form of the dacite magma body cannot be determined due to the structural complexity of this area, but a partly emergent dome or cryptodome is suggested in Figure 10.

The breccia at Locality 12 is tentatively interpreted as a marginal, completely disaggregated facies of the Peldar Dacite Breccia, either a peperite or a subaqueous debris flow. The developments of Peldar Dacite Breccia within the volcaniclastic screen in the northern part of Whitwick Quarry may similarly argue for a local extrusive component of this magmatism, compatible with the activity of a partly emergent dome. The origin of these screens is largely obscured by deformation, however, and it is equally possible that they are intrusive peperites, representing tongues of dacitic magma that extended into, and reacted with, an unconsolidated sedimentary host.

Proximal volcaniclastic strata of the Charnwood Lodge Volcanic Formation

This formation includes the Cademan Breccia and Swannymote Breccia members, which were described earlier. Here are described the undivided part of the formation, as well as the *Benscliffe Breccia Member* and *St. Bernard Tuff Member*.

The undivided part of this formation consists of interbedded tuffs, lapilli-tuffs and breccias (Fig. 1). The Gunhill Rough (Loc. 13) and Charnwood Tower (Loc.14) exposures show a diverse succession of poorly sorted breccias intercalated with thinly stratified lithic-lapilli tuffs and coarse-grained lithic-crystal tuffs (Fig. 7). At Gunhill Rough, the upper breccia bed is normally graded, with the larger subrounded andesite blocks (up to 0.7 m size) near the base. In contrast, size sorting in the lower breccia features blocks concentrated into discrete layers above the basal part of the bed, defining a parallel-stratified internal structure. The intervening tuffs include layers that show both normal and inverse grading. In thin section, a block from a Gunhill breccia has a fine-grained intergranular groundmass texture, with abundant small plagioclase laths and microlites arranged in fluxional orientation; it also contains up to 30% of strongly zoned and generally euhedral plagioclase phenocrysts, rare quartz microphenocrysts and small, rounded inclusions of microgranular diorite. The breccia matrix contains much recrystallized, fine-grained quartzo-feldspathic material, but the outlines of plagioclase crystals and angular slivers of granular-textured microdiorite remain visible. Angular, microcrystalline-textured lapilli also comprise many of the lithic clasts in the parallel stratified and graded beds of Gunhill Rough.

The middle to upper part of the Charnwood Lodge Formation (Fig. 1) includes, at the Charnwood Lodge Nature Reserve SSSI, the prominent knoll (Loc. 15) which is the classic 'Bomb rocks' locality of Watts (1947). These rocks contain abundant blocks with ovoid to rectangular or diamond shaped outlines, and the lithology is a volcanic breccia in most modern classifications (Fisher, 1961; Fisher and Schmincke, 1984). The example shown in Figure 8a contains about 60 per cent of andesite blocks, up to 1 m size (average about 0.6 m), some being angular but others, more abraded, featuring rounded-off corners. This breccia appears to be unbedded, and hence similar to many parts of the Cademan Breccia Member; however, within a few tens of metres of the knoll it shows variations in clast to matrix proportions, and in clast size. For example, strongly clast-supported breccias, containing abundant closely-packed but relatively small blocks (Fig. 8b), are seen along the northern margin of the exposure. The 'bomb rocks' may therefore exhibit a very coarsely developed type of size grading of the clasts, which in turn suggests it forms part of a thickly stratified sequence.

Chemical analysis shows that a typical block sampled from a breccia at the Gunhill Rough locality is an andesite, with 57.6% SiO2. Some diversity of clast lithologies within the Charnwood

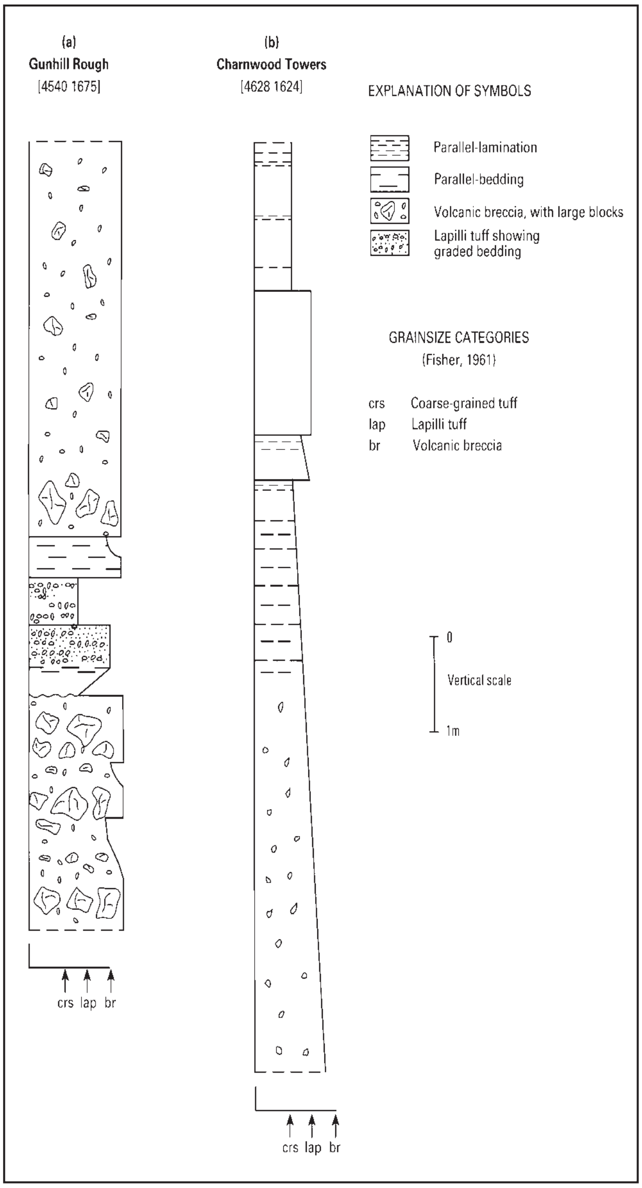

Figure 7. Measured sections showing lithological variations that produce stratification in the undivided part of the Charnwood Lodge Volcanic Formation.

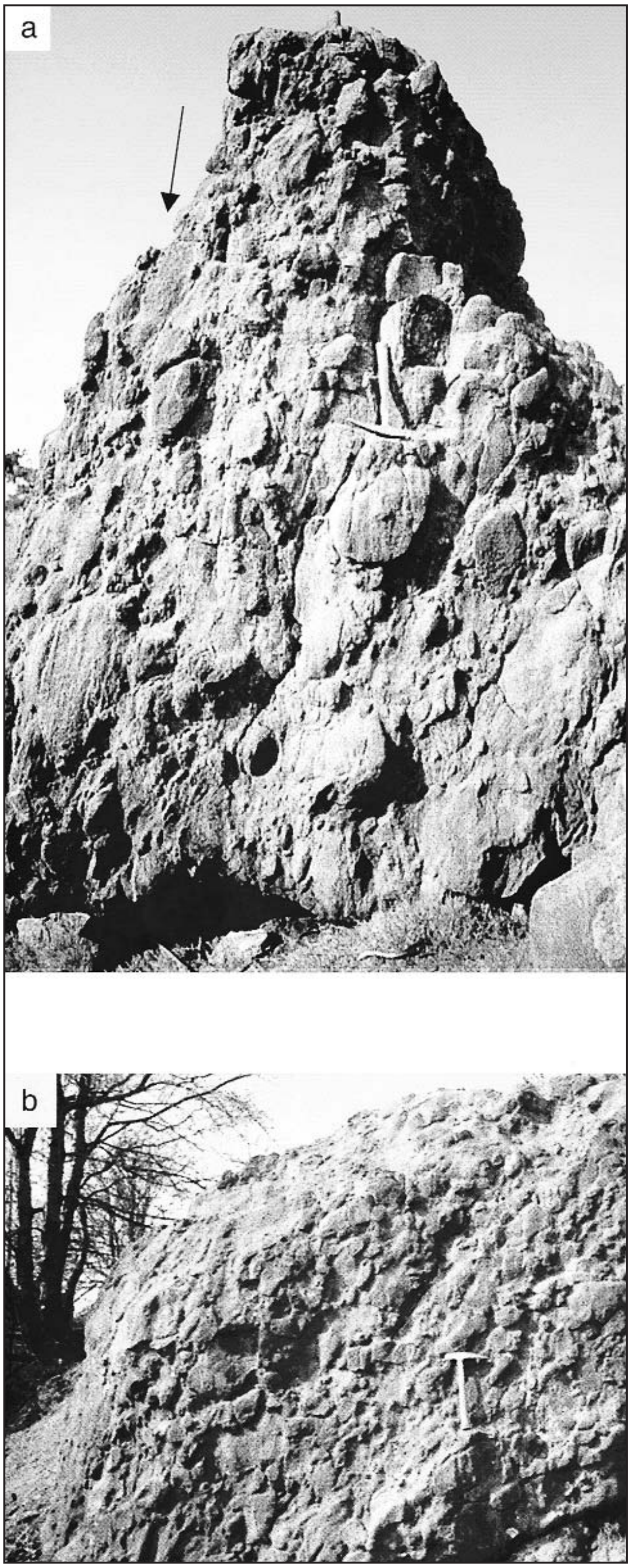

Figure 8. Volcanic breccias of the Charnwood Lodge Volcanic Formation exposed at the 'Bomb rocks' locality, Charnwood Lodge Nature Reserve (463157) **a.** Breccia at the main knoll, showing large subangular andesite or (low-silica) dacite blocks, slightly flattened in the plane of the subvertical Acadian (Silurian-Devonian) cleavage, the orientation of which is given by the arrow. **b.** A breccia, about 40 m north-east of the main knoll, with smaller, more closely-packed blocks.

Lodge Formation is suggested by a further analysed block, from the breccia outcrop across the fault to the east of Whitwick Quarry (Loc. 16); on grounds of chemistry at least, this is a rhyolite, with 76.5 % silica (unpublished BGS analyses, adjusted for volatiles content). Two analysed samples of breccia matrix from the Charnwood Lodge area showed silica contents of between 60 and 65% (Moseley and Ford, 1989), in keeping with the transitional andesite/dacite compositions inferred for most of the blocks in the Charnwood Lodge Formation.

The top of the Charnwood Lodge Formation is exposed at Warren Hills ridge (Loc. 17). Here the unit has fined down, to a succession of massive to stratified, coarse-grained tuffs and lapilli-tuffs, with only subordinate intercalations of matrix-supported breccia. The stratigraphically highest lapilli-tuff beds contain sporadic, ellipsoidal fragments of laminated volcaniclastic siltstone or mudstone. These fragments become larger and more numerous in beds just below the volcaniclastic sandstones of the Bradgate Formation, developing into a sediment-raft breccia in which slivers of pale grey volcaniclastic siltstone, between 2 and 10 centimetres thick, show contortion and folding in a coarse-grained, crystal-rich volcaniclastic matrix.

The Benscliffe Breccia Member occupies the base of the Maplewell Group, and when traced around the nose of the Charnian anticline it thickens towards the northwest. In the study area the member is lithologically indistinguishable from the undivided part of the Charnwood Lodge Formation (Table 3), with which it is considered to merge (Fig. 1). On the southeastern flank of Flat Hill, the outcrop mapped as 'Benscliffe Agglomerate' by Worssam and Old (1988) consists of at least 100 m of interstratified lithic-lapilli tuff and volcanic breccia. Subtle variations in clast size and abundance suggest that several fining upward cycles may be present in this succession. For example, at Hanging Stone (Loc. 18), the lower part is a breccia containing about 40% of angular to subrounded clasts of grey, feldsparphyric andesite. There is then an upward gradation into about 5 m of lapilli tuffs. A further exposure, several metres stratigraphically higher than this, shows a similar passage from volcanic breccia at the base to lapilli-tuff, with only sporadic angular lapilli and blocks (5-10 cm size), at the top. Younger beds still, to the southwest (467159), feature breccias with subangular, cream-weathering, feldsparphyric andesite blocks up to 0.5 m across, which passes upwards into thickly bedded lithic-lapilli tuff.

The St. Bernard Tuff Member was named by Carney (1994), and consists of about 100 m of stratified, fine- to coarse-grained tuffs occurring in the vicinity of Mount St. Bernard Monastery (Loc. 19). Local bedding dips suggest that this unit may be contained within a syncline or basin, which closes to the northwest of the Monastery. The beds immediately below the member are exposed in the Monastery grounds to the northeast of the crags at Calvary; they are unusual for this region in consisting of pale grey, thinly bedded to laminated volcaniclastic siltstone. They are overlain by a homogeneous, pale grey, massive lithic-crystal tuff, or lapilli-tuff, which at c. 60 m thick forms the main part of the member. On fresh surfaces this rock has abundant large white or pink feldspar crystals, etched out by weathering. Thin sections show that in addition to these plagioclase crystals, the tuff contains lapilli of microcrystalline andesite or dacite. The succession is capped by 3 m of grey-green crystal-lapilli tuff containing about 40 per cent of pinkish grey plagioclase feldspar crystals; a thin section showed common lapilli of microcrystalline dacite with possible relict vesicles, although most textural features are hidden by secondary recrystallization. Crags a few metres northeast of the Abbey wall show that the stratigraphically youngest part of the St Bernard Tuff Member consists of stratified, feldspar-rich crystal tuff which passes up to thinly bedded, repetitively graded, crystal tuff.

Interpretation of the Charnwood Lodge Volcanic Formation. With the exceptions of the Cademan and Swannymote breccias, described earlier, this formation is characterised by thickly bedded breccias and lapilli-tuffs. The low degree of sorting in the stratified breccia component, together with the occurrence of angular or subangular blocks of variable size within a coarse-grained matrix, are features found in mud-poor, cohesionless debris flows, or the 'gravelly high-density turbidity currents' of Lowe (1982). They imply very rapid transport and deposition with only localised abrasion, or transport over limited distances, with abrasion localised at the corners of blocks due to collisions with other clasts. The parallel bedding and variously graded lapilli-tuffs intercalated with the breccias (Fig. 7) are better-organised. They resemble the tractional division that is typically present at the base or the top of cohesionless debris flow deposits considered by Postma *et al* (1988), but are also akin to the deposits of residual, high-density sandy turbidites that have by-passed areas of breccia deposition (Lowe, 1982).

Cohesionless debris flows are characterised by a granular matrix with very little mud component; however, the occurrence of entrapped mud- or fine-ash-grade material in at least some of these Charnian lithologies cannot be ruled out. Such constituents would be difficult to detect now, because of the high degree of recrystallization that these rocks have suffered. It is noteworthy that only small proportions of these fines would be required for an alternative interpretation of some fragmental lithologies as the derivatives of cohesive debris flows, or mud-rich debris flows (Hampton, 1975). In the Charnian context these deposits, being rich in volcanic detritus, would further qualify as the representatives of 'lahars', which are essentially volcaniclastic debris flows (e.g. Cas and Wright, 1987). Lahars can form at all scales, but they are commonly generated by large-scale collapse of the volcano flanks, as shown in Figure 10, and they consequently sample a more lithologically diverse source region than do dome-derived block and ash pyroclastic flows. This may explain some of the analysed blocks that indicate a relatively large compositional range of included detritus in the Charnwood Lodge Formation.

Some sedimentary debris flows form within subaqueous deltas that receive material from a steeply sloping, emergent hinterland (e.g. Kim *et al.*, 1995; Postma *et al*; 1988). No criteria have yet been found to either support or militate against a waterlain origin for the Charnian material. However, the volcaniclastic sequences that both underlie (Blackbrook Group) and succceed (Bradgate Formation) them are thought to be entirely subaqueous (Moseley and Ford, 1989). Thus the most likely environment for the Charnwood Lodge Formation is that of a subaqueous volcaniclastic apron deposited adjacent to a Charnian volcanic centre.

The most proximal rocks of the Charnwood Lodge Formation are the Cademan and Swannymote breccias, and as discussed these probably represent the deposits of primary pyroclastic flows derived from dome-collapse eruptions. According to Cas and Wright (1991), pyroclastic flows upon entering water may split into separate components. The fine ashy material, would be separated at the air-water interface, either as eruption clouds or low-density overflows, and might be represented in the more distal-facies rocks of the Beacon Hill Formation (Fig. 1). The dense-clast-rich part may continue to run out as a subaqueous flow of pyroclastic debris. It is therefore conceivable that some of the interstratified volcanic breccias and tuff sequences of the Charnwood Lodge Formation may represent the resedimented, syn-eruptive products (McPhie *et al.*, 1993; p.98) of 'Cademan' type dome-collapse events.

The thickness and fining upward evolution of the St Bernard Tuff Member are features that recall the graded, predominantly coarse-grained, pyroclastic sequences found in some young volcanic arcs. For example, Fiske and Matsuda (1964) describe from the Miocene of Japan an analogous sequence, the Tokiwa Formation, consisting of a very thick (45 m) unbedded dacitic lapilli tuff capped by 7-15 m of parallel-stratified and multiply-graded turbidite-facies tuffs composed of sand-size ash and crystal fragments. The origin of the Tokiwa Formation is enigmatic, but has been linked to mechanisms associated with subaqueous pyroclastic eruptions (Cas and Wright, 1991).

Geochemistry of the igneous rocks

Pharaoh *et al.* (1987) used geochemistry to determine the tectonic setting of the Charnian igneous rocks. Their studies showed that typical compositions have a strong subduction zone signature and are comparable to magmas erupted from modern volcanic arcs, including island arc chains, of a type founded upon oceanic or thin continental crust. In this section, geochemistry is mainly used to describe the compositional range of the Whitwick Volcanic Complex and Charnwood Lodge Volcanic Formation, and to compare and evaluate the relationships between these rocks, particularly those of the two genetic associations (Table 1). Representative chemical compositions are shown in Table 2; the full data set consists of only 20 samples, so the following discussion should not be interpreted as an in-depth geochemical treatment of these rocks.

The samples collected from northwestern Charnwood Forest are plotted on the TAS (total alkalies vs silica) diagram (Fig. 9a), which shows that with a single exception, these rocks encompass the andesite, dacite and rhyolite compositional fields. The most silica-rich compositions, with rhyolites represented, are restricted to the porphyritic Sharpley/Swannymote association. It should be noted that the TAS diagram may be of doubtful value for classifying these fine-grained rocks, because it is based on elements whose relative proportions are likely to be affected by secondary processes. For example, Table 2 shows wide variations in the contents of Na_2O and K_2O, the latter in particular being anomalously low in some samples, as is the related trace element, Rb. The

	Grimley Andesite breccia*	Grimley Andesite dyke	Dacite, in Cademan VBM*	Dacite, in Peldar DB*	Sharpley Porphyritic Dacite	Rhyolite, in Swannymote BM*
sample	JNC536	JNC548	JNC528	JNC531A	EM1	JNC499
NGR	447162	447159	434168	483158	448171	447163
%						
SiO_2	55.95	61.01	64.57	67.58	72.11	76.73
TiO_2	0.52	0.43	0.39	0.38	0.36	0.26
Al_2O_3	16.85	14.74	13.89	13.31	13.15	12.09
Fe_2O_3t	9.21	7.47	6.31	5.45	4.11	1.94
MnO	0.24	0.15	0.12	0.07	0.09	0.02
MgO	5.38	3.79	3.54	2.81	2.36	0.57
CaO	2.09	5.27	3.95	4.18	0.49	0.78
Na_2O	2.95	3.26	2.96	2.46	7.22	6.19
K_2O	2.39	0.24	1.73	0.67	0.09	0.25
P_2O_5	0.06	0.05	0.05	0.06	0.07	0.06
loi	4.14	3.33	2.27	2.17	nd	0.53
ppm						
Ba	865	97	489	250	60	68
Ce	8	12	7	16	28	15
Co	nd	26	22	16	7	4
Rb	49	nd	nd	12	2	2
Sr	40	75	70	78	55	73
V	368	173	165	97	38	35
Y	19	20	16	23	32	19
Zr	59	55	44	62	77	52
La	4	3	3	8	8	8
Nd	6	5	9	9	12	9

Table 2. Representative chemical compositions of rocks from the Whitwick Volcanic Complex and Charnwood Lodge Volcanic Formation (see Table 1 for lithostratigraphy). Analysed by XRF at BGS, except EM1 by P. C. Webb.
* — sample is from a block or fragment within a breccia

causes of these variations are attributed to element mobility, which can occur in a variety of environments. For example, in the late-magmatic environment hot rocks may chemically interact with the vapour phase of the magma, or with meteoric water or seawater. Similarly, in the immediately post-emplacement environment relatively slowly cooled rocks, such as the matrix and clast components of pyroclastic deposits, can also suffer complex element exchanges due to varying degrees of hydration (Jørgensen and Holm, 1998). Finally, element mobility is common during metamorphism and could have accompanied the episode of greenschist-facies recrystallization in these Charnian rocks.

Although the TAS diagram may not reflect primary magmatic element abundances, and must be viewed with caution as an aid to rock classification, it nevertheless does portray the generally close chemical equivalence of the lithological pairings that constitute the two genetic associations. The two fragmental components of these associations (Cademan Breccia and Swannymote Breccia) are nevertheless more silicic than their putative parental material (respectively the Grimley Andesite and Sharpley Dacite). The reasons for this discrepancy, discussed further below; may lie in post-magmatic chemical exchanges of the type already mentioned, and cannot be evaluated without a more rigorous geochemical study.

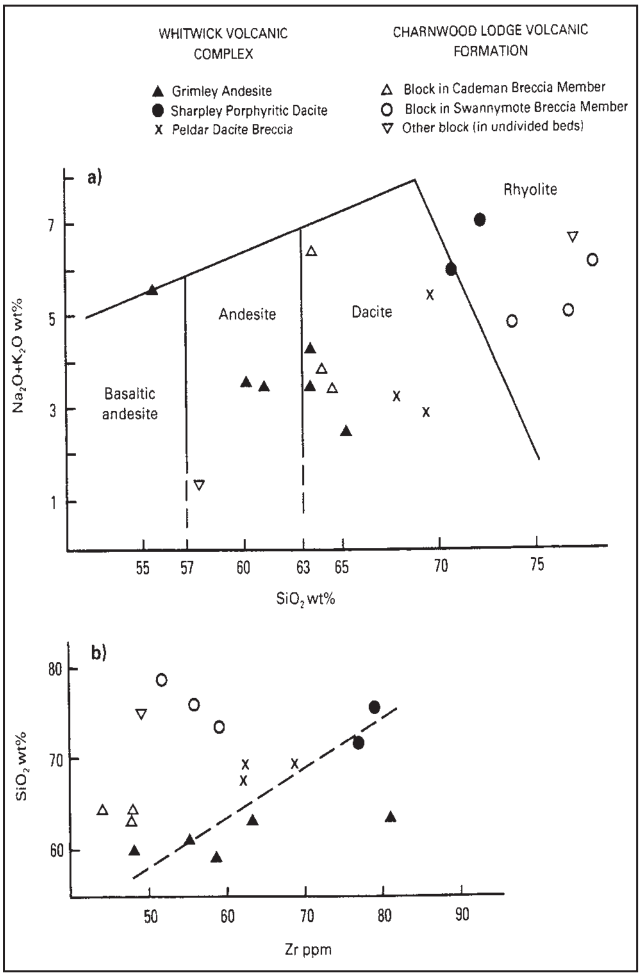

Figure 9. Major and trace element variations in the rocks of the study area. Compiled from BGS data and two analyses provided by P. C. Webb.
a. Plot of total alkalies vs silica, re-calculated on a volatiles-free basis, showing the compositional fields defined by Le Bas and Streckeisen (1991).
b. Plot of silica vs zirconium; dashed line shows the 'best fit' for the variation trend between rocks of the Whitwick Volcanic Complex.

For interpreting geochemical relationships, more reliance is generally placed on the relatively 'immobile' High Field Strength Elements (HFSE), also known as Incompatible Trace Elements (ITEs), which are resistant to the effects of low-temperature alteration and metamorphism (e.g. Pearce and Cann, 1973). Of these, Zr is relatively incompatible with most crystallizing phases (excluding zircon, see below) in a melt and consequently, in certain volcanic sequences, it has been used as an index of differentiation. In this case Zr abundances should increase in the more fractionated rocks, in the same way that SiO_2 generally does, but without random variations caused by secondary element redistribution. Plotting these two elements together (Fig. 9b) is a simple way of testing whether Zr and SiO_2 both act as reliable differentiation indicators, because if they do a linear trend should result. This plot shows that a reasonably linear trend can be drawn between the various components of the Whitwick Complex, with Zr abundances increasing in line with SiO_2, from the Grimley Andesite via the Peldar Dacite to the Sharpley Dacite. The breccia blocks of the two associations plot off this trend, with lower Zr than their putative parental igneous rocks in the Whitwick Volcanic Complex. It is possible that both the silica and Zr distributions of the breccia blocks in Figure 9b could be explained by invoking element gains (e.g. silica) or losses (e.g. zirconium) in the immediate post-magmatic environment, as discussed earlier. An alternative possibility is that the breccia blocks were derived from magmas that were slightly less evolved (in terms of their Zr contents) than those supplying the Grimley Andesite or Sharpley Dacite. This would be a complication to the model of Figure 10, and would imply that multiple generations of magma have occurred. Finally, it is possible that the Zr contents were lowered in the syn-magmatic environment due to the crystallisation of zircon. This would impoverish Zr in the more 'evolved' differentiates that here are represented by the blocks of the Cademan and Swannymote breccias. Although such zircon fractionation cannot be ruled out, it is a fact that no zircons have been observed in these particular Charnian rocks; for example, several kilograms of Sharpley Dacite were recently crushed for geochronological analysis (work in progress by BGS and NIGL), and not one zircon grain was obtained.

Discussion and review of Charnian igneous processes

Precambrian magmatism centred upon north-western Charnwood Forest has produced two fundamentally different, but nevertheless closely linked rock sequences. The processes that were involved are summarised in Figure 10, which views the igneous rocks of the Whitwick Volcanic Complex as the remnants of a magmatic feeder zone that contributed material to a flanking sequence represented by the Charnwood Lodge Volcanic Formation (Fig. 10). Although the origin of these rocks remains obscure, none are likely to be unique in the geological record and analogies for some of them may be sought in the diverse magmatic products of modern volcanic arcs. W. W. Watts (1947) used this approach when he presciently suggested that certain fragmental Charnian rocks were comparable to deposits formed by the catastrophic 1902 eruptions of Mont Pelée, some being originally '*...of the nature of the "spine" intruded and extruded in the later stages of the eruption of Mont Pelee in 1902, the breaking up of it, such as then occurred, would give rise to aggregates of great "bombs"...*'.

Problems with interpreting these rocks are partly due to the wide compositional range, and consequent diversity of physical properties, exhibited by the Charnian magmas. Such variations had an influence on emplacement mechanisms and, as modelled in Figure 10, the environments in which the magmas consolidated were correspondingly diverse and ranged from subaerial, to partly or wholly 'intrusive' in the case of the Sharpley/Swannymote Association and the Peldar Dacite Breccia. The latter have the most silicic compositions, possess abundant phenocrysts, and in consequence they would have formed viscous magmas. This may explain why they largely failed to reach the surface and instead consolidated as intrusive sheets or cryptodomes. The porphyritic dacites were therefore not important suppliers of volcanic material to the part of the Charnwood Lodge Volcanic Formation that is now exposed.

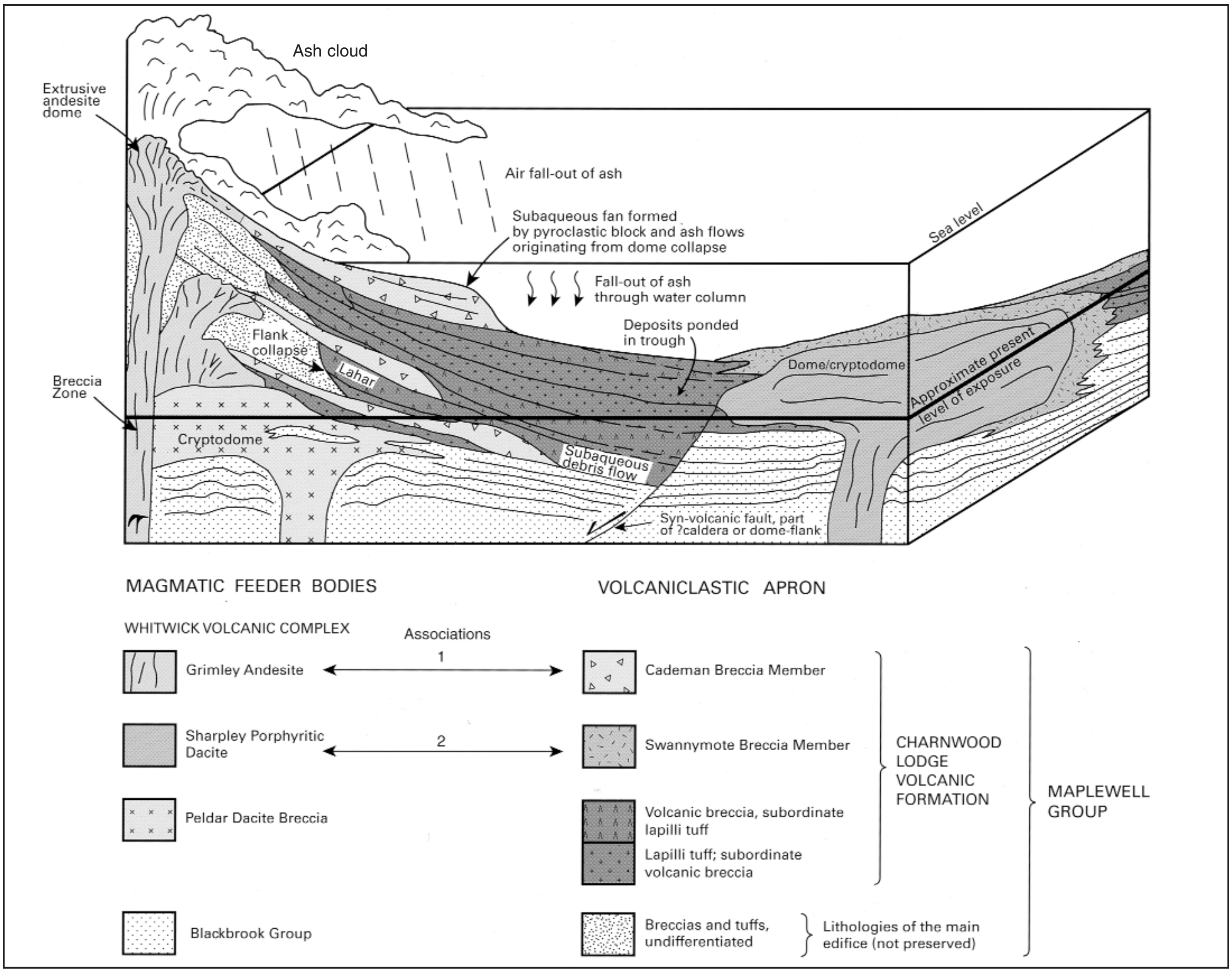

Figure 10. Simplified model showing the range of volcanic and depositional processes likely to have been occurring during the late Precambrian active phase of northwest Charnian magmatism. Note that this diagram is not intended to explain all of the field relationships depicted in Figure 1.

Table 3. Summary of the main lithological features and interpretations of the rocks in the study area.

UNIT	DESCRIPTION	INTERPRETATION
WHITWICK VOLCANIC COMPLEX		
GRIMLEY ANDESITE	Grey-green, smooth-surfaced, microcrystalline, sparsely to moderately porphyritic (plagioclase, hornblende, minor quartz). Compositional range: high-silica andesite to low-silica dacite. Massive in places, but more commonly highly brecciated, with jigsaw fit of fragments. Up to 940 m thick.	High-level intrusion, possibly the root-zone of a subaerial extrusive dome affected by multiple fracturing during extrusion and/or inflation
SHARPLEY PORPHYRITIC DACITE	Pale grey to lavender, rough-surfaced, microcrystalline and highly porphyritic (plagioclase-quartz). Compositional range: dacite verging to rhyolite. Massive, locally columnar-jointed. Possible marginal breccia or pseudo-breccias. Up to 600 m thick	High-level intrusive sheet or cryptodome. Emplaced largely below sea-floor and marginally brecciated due to reaction with partly unconsolidated sediment
PELDAR DACITE BRECCIA	Dark grey to black, pervasively brecciated, with rounded to cuspate-margined masses of highly porphyritic (plagioclase-quartz) dacite in a grey, medium-grained, clastic matrix full of spherulitic-textured glassy fragments. Up to 520 m thick.	Cryptodome, emplaced at shallow depths below sea-floor and extensively disaggregated due to reaction with enclosing carapace of unconsolidated sediment.
CHARNWOOD LODGE VOLCANIC FORMATION		
CADEMAN VOLCANIC BRECCIA MEMBER	Very coarse, poorly sorted volcanic breccias packed with angular to subangular blocks of microcrystalline, low-silica dacite. Outsized blocks and jigsaw-fit textures locally observed. Structureless, apart from variations in clast to matrix proportions. Up to 450 m thick.	Merapi-type block and ash pyroclastic flows, derived from collapse of 'Grimley' type domes. Possible subaqueous deposition on pyroclastic fan and/or 'ponded' in caldera.
SWANNYMOTE BRECCIA MEMBER	Very coarse, poorly sorted volcanic breccias, with angular, rounded or cuspate-margined blocks of microcrystalline to spherulitic, porphyritic (plagioclase-quartz) rhyolite. Locally with admixed sediment or sedimentary clasts. Up to ?200 m thick.	Ash and block pyroclastic flows and peperite breccias derived from marginal fragmentation of 'Sharpley' domes or cryptodomes.
BENSCLIFFE BRECCIA & UNDIVIDED BEDS	Thickly stratified and locally graded sequences of andesitic volcanic breccia and parallel-stratified lithic-crystal-lapilli tuff. Fines up to overlying Bradgate Formation. 900-1000 m thick locally.	Cohesionless and cohesive debris flows of volcaniclastic material; includes deposits of lahars and re-sedimented 'Cademan'-type pyroclastic flows. Probable subaqueous depositional environment
St BERNARD TUFF MEMBER	Mainly composed of massive, lithic-crystal tuff and lapilli-tuff. Fines up to a capping of thinly- bedded graded crystal tuff. About 100 m thick.	? Deposit of major subaqueous pyroclastic eruption

Their emplacement would have both displaced and dewatered the host sediments, however, producing a rigid platform on which the emergent andesitic centres of the Grimley/Cademan Association were built.

The term 'intrusive' is used advisedly for the Peldar and Sharpley rocks, since as noted they were shallowly emplaced, into a column of unconsolidated wet sediments. Physical interactions between magma and sedimentary host occurred on a massive scale in order to cause the pervasive disaggregation that is such a feature of the Peldar Dacite Breccia. In this condition, the breccia would have been capable of secondary flowage, and could have back-intruded its host, to form the posssible peperite-breccia layers interbedded with the volcaniclastic rocks in Whitwick Quarry. The Sharpley Porphyritic Dacite is by contrast a largely homogeneous lithology, although it does show marginal brecciation and clearly contributed blocks to the adjacent Swannymote Breccia Member. Limited intermingling between magma and wet sediment accounts for some of the lithologies at Swannymote Rock, but the consolidated state of the sediment incorporated at Ratchet Hill suggests that the heat of dacite intrusion had dewatered parts of the sedimentary substrate. The Sharpley magma was therefore able to solidify as a relatively coherent body, perhaps an intrusive sheet or cryptodome.

The shallow-depth intrusive environment of the Sharpley/Swannymote Association and the Peldar Dacite Breccia may have produced vesicular or pumiceous lithologies, due to the release of exsolved gases under conditions of low confining pressures. The absence of such features indicates suppression of vesiculation upon chilling, in favour of spherulitic crystallisation, and may suggest that the magmas had been slowly degassed during their uprise. Alternatively, it is possible that in spite of the relatively shallow level of intrusion, the confining pressures were still high enough to prevent gas escape. In the Charnian context, there are no reliable indicators (e.g. fossils) for estimating either the water or sedimentary overburden depths that would have influenced the confining pressure. In a case study on Permian-age volcanics by Hunns and McPhie (1999), however, it was suggested that for rhyolitic magmas of average water content (about 3%) a combination of 200 m water depth and a sedimentary thickness in excess of 400 m was necessary to suppress explosive vesiculation upon emplacement. Other examples previously discussed are from young (Mesozoic and Cainozoic) volcanic arcs whose activity is similarly well constrained. Such sequences include homogeneous silicic intrusions and marginal peperite breccias, some of which were emplaced within cryptodomes that were enclosed, and largely insulated, by a thick column of water-saturated sediments.

High-level intrusion of the Peldar and Sharpley porphyritic dacites is in keeping with the stratigraphical relationships, summarised in Figure 10, which indicate that these magmas encountered the upper parts of a volcaniclastic sedimentary sequence at least 2000 metres thick, represented by the Blackbrook Group. It is noteworthy that although the Blackbrook Group strata are composed entirely of volcanic material, sedimentary structures show that they are mainly of distal turbidite facies (Moseley and Ford, 1989; Carney, 1994) suggesting their deposition at some distance from the then-active volcanic centres. Formation of the igneous and proximal volcaniclastic rocks, discussed here, therefore followed a major change in the location of the Charnian magma source(s). This may have involved either a renewal of magmatism, or an extension of the magmatic axis into this region, and the causes may lie in readjustments to the plate-tectonic configuration of the Charnian arc as it entered the final stage of extrusive activity.

The Grimley Andesite and Cademan Breccia are interpreted here as the complementary products of dome-sourced eruptions (Fig. 10), and this is the main reason for comparing them with the recent activity on Montserrat (Young *et al.*, 1998). This style of Charnian volcanism may be further assessed by considering the nature of the extrusive dome material represented by blocks in the pyroclastic rocks of the Cademan Volcanic Breccia Member. In that unit, virtually all of the low-silica dacite blocks or lapilli consist of 'dense' (non-vesicular) lithologies, indicating that the causative eruptions were probably of 'Merapi' type (Williams and McBirney, 1979, p.152; see also discussion in Young *et al.*, 1998). Such activity is generally non-explosive, owing to the low content of gas remaining in the magma, and the block and ash pyroclastic flows result from gravity-collapse of the oversteepened flanks of the domes. This analogy suggests that the Grimley Andesite magmas may have been degassed during protracted cooling and high-level crystallization, causing microcrystalline and cryptocrystalline textures to develop, as the magma ascended and solidified. Peléan-type eruptions, on the other hand, are blast-induced and tend to involve more gas-rich, pumiceous material, although this is not always the case.

The Montserrat analogy proposed the Grimley/Cademan Association implies that dome extrusion occurred through subaerial volcanic edifices. At the present level of erosion, the rock sequences that might have formed these superstructures are not preserved (Fig. 10), which could suggest their prior removal by denudation. In modern intra-oceanic volcanic arcs, emergent andesitic edifices can occupy appreciable surface areas (about 70 km^2 for the active Soufrière Hills Volcano on Montserrat), but relative to many geological formations they are easy to erode and consequently difficult to preserve in the geological record. Erosion of the extinct Grimley edifice(s) may have continued until the Lower Cambrian marine transgression across central England, which has been timed at approximately Tommotian, or about 530-535 Ma, at Nuneaton, 40 km to the south (Brasier, 1992). The date of volcanic cessation is unfortunately not precisely constrained for the Charnian; it could be as old as about 600 Ma, or as young as 560 Ma (see discussion in McIlroy *et al.*, 1998). These estimates allow a duration of 30-70 million years for this erosion.

The model in Figure 10 shows that some of the extrusive products of Whitwick Complex volcanism could be preserved in the Charnwood Lodge Volcanic Formation. The coarsely fragmental lithologies of that unit can broadly be interpreted as mass flows of volcanic debris, but exposures are generally too limited to determine their specific modes of origin. It is nevertheless possible that lahar deposits, in part triggered by volcano-flank collapses, are represented, as are the deposits of block and ash pyroclastic flows (Cademan Breccia) derived from the collapse of 'Grimley'-type extrusive domes. Similar successions characterise the medial or distal ring plain sequences surrounding modern andesitic composite volcanoes. For example, at Ruapehu Volcano in New Zealand, the ring plain consists of 'lensoid, coarse-grained volcaniclastic deposits, comprising both matrix-rich and laharic deposits and better sorted fluvial sediments' (Hackett and Houghton, 1989). The obvious lack of fluvial sediments here, combined with the evidence that the volcaniclastic units both above and below the Charnwood Lodge Formation are probably entirely waterlain, suggests that the Charnian 'ring plain' equivalent must have been accumulated subaqueously (Fig. 10). In this type of environment the blocky fragmental material derived from lahars, or various other forms of subaerial volcaniclastic debris avalanches, or from pyroclastic flows, may have entered water and transformed into subaqueous volcaniclastic debris flows. Modern sedimentological studies provide an explanation for some of the finer-scale stratification that has been described; they have shown that rock avalanches (pyroclastic flows or lahars) can grade into stratified debris flows with increased distance from the source, particularly if the runout is within standing water (Yarnold, 1993).

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References

Bennett, P. W., Lowe, E. E., Gregory, H. H. and Jones, F., 1928. The geology of Charnwood Forest. *Proceedings of the Geologists' Association*, **39**, 241-97.

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

Brasier, M. D., 1992. Background to the Cambrian explosion. *Journal of the Geological Society of London*, **149**, 585-587.

Carney, J. N., 1994. Geology of the Thringstone, Shepshed and Loughborough districts (SK41NW, SK41NE and SK51NW). *British Geological Survey Technical Report* WA/94/08.

Carney, J. N., 1999. Revisiting the Charnian Supergroup: new advances in understanding old rocks. *Geology Today*, **15**, 221-229.

Carney, J. N. and Pharaoh, T. C., 2000. Bardon Hill. In, *Precambrian Rocks of England and Wales*, Geological Conservation Review Series, **20**. Joint Nature Conservation Committee, Peterborough, 40-43.

Cole, P. D., Calder, E. S., Druitt, T. H., Hoblitt, R., Robertson, R., Sparks, R. S. J. and Young, S. R., 1998. Pyroclastic flows generated by gravitational instability of the 1996-97 lava dome of Soufriere Hills Volcano, Montserrat. *Geophysical Research Letters*, **25**(18&19), 3425-3428.

Cas, R. A. F. and Wright, J. V., 1987. *Volcanic successions: modern and ancient: a geological approach to processes, products and successions*. Allen and Unwin, London, 528 pp.

Cas, R. A. F. and Wright, J. V., 1991. Subaqueous pyroclastic flows and ignimbrites: an assessment. *Bulletin of Volcanology*, **53**, 357-380.

Fisher, R. V., 1961. Proposed classification of volcaniclastic rocks. *Geological Society of America Bulletin*, **72**, 1409-1414.

Fisher, R. V. and Schmincke, H-U., 1984. *Pyroclastic Rocks*. Springer-Verlag, New York, 472 pp.

Fiske, R. S. and Matsuda, T., 1964. Submarine equivalents of ash flows in the Tokiwa Formation, Japan. *American Journal of Science*, **262**, 76-106.

Hackett, W. R. and Houghton, B. F., 1989. A facies model for a Quaternary andesitic composite volcano: Ruahepu, New Zealand. *Bulletin of Volcanology*, **51**, 51-68.

Hampton, M. A., 1975. Competence of fine-grained debris flow. *Journal of Sedimentary Petrology*, **45**, 834-844.

Hanson, R. E., 1991. Quenching and hydroclastic disruption of andesitic to rhyolitic intrusions in a submarine island-arc sequence, northern Sierra Nevada, California. *Geological Society of America Bulletin*, **103**, 804-816.

Hanson, R. E. and Wilson, T. J., 1993. Large-scale rhyolite peperites (Jurassic, southern Chile). *Journal of Volcanology and Geothermal Research*, **54**, 247-264.

Hill, E. and Bonney, T. G., 1891. On the northwest region of Charnwood Forest, with other notes. *Quarterly Journal of the Geological Society of London*, **42**, 78-100.

Hunns, S. R. and McPhie, J., 1999. Pumiceous peperite in a submarine volcanic succession at Mount Chalmers, Queensland, Australia. *Journ. Volcanology Geothermal Research*, **88**, 239-254.

Jones, F., 1926. The petrology and structure of the Charnian rocks of Bardon Hill. *Geological Magazine*, **63**, 241-55.

Jørgensen, J. Ø. and Holm, P. M., 1998. Progressive alkali ion exchange with stratigraphic position in a pyroclastic cooling-unit; Mt. Torro, Sabatini, Central Italy. *Journal of Volcanology and Geothermal Research*, **86**, 179-185.

Kim, S. B., Chough, S. K. and Chun, S. S., 1995. Bouldery deposits in the lowermost part of the Cretaceous Kyokpori Formation, SW Korea: cohesionless debris flows and debris falls on a steep-gradient delta slope. *Sedimentary Geology*, **98**, 97-119.

Kokelaar, B. P., 1986. Magma-water interactions in subaqueous and emergent basaltic volcanism. *Bulletin Volcanology*, **48**, 275-289.

Le Bas, M. J. and Streckeisen, A. L., 1991. The IUGS systematics of igneous rocks. *Journal of the Geological Society*, **148**, 825-833.

Lowe, D. R., 1982. Sediment gravity flows: II, depositional models with special reference to the deposits of high density turbidity currents. *Journal of Sedimentary Petrology*, **52**, 279-297.

Lofgren, G., 1971. Experimentally produced devitrification textures in natural rhyolitic glass. *Bull. Geol. Soc. America*, **72**, 111-124.

McArthur, A. N., Cas, R. A. F. and Orton, G. J., 1998. Distribution and significance of crystalline, perlitic and vesicular textures in the Ordovician Garth Tuff . *Bulletin Volcanology*, **60**, 260-285.

McIlroy, D., Brasier, M. D. and Moseley, J. M., 1998. The Proterozoic-Cambrian transition within the 'Charnian Supergroup' of central England and the antiquity of the Ediacara fauna. *Journal of the Geological Society London*, **155**, 401-413.

McPhie, J., Doyle, M. and Allen, R. 1993. *Volcanic textures: a guide to the interpretation of textures in volcanic rocks*. (Government Printing Office, Tasmania) 198 pp.

Merriman, R. J. and Kemp, S. J., 1997. Metamorphism of the Charnian Supergroup in the Loughborough District, 1:50K Sheet 141. *British Geological Survey Technical Report* WG/97/7.

Miller, A. D. and eight others, 1998. Seismicity associated with dome growth and collapse at the Soufriere Hills volcano, Montserrat. *Geophysical Research Letters*, **25**, 3401-3404.

Moseley, J. B. and Ford, T. D., 1985. A stratigraphic revision of the Late Precambrian rocks of the Charnwood Forest, Leicestershire. *Mercian Geologist*, **10**, 1-18.

Moseley, J. B. and Ford, T. D., 1989. The sedimentology of the Charnian Supergroup. *Mercian Geologist*, **11**, 251-274.

Murphy, M. T. and Marsh, B. D., 1993. Textures and magmatic evolution of intermediate-composition dome complexes: Evidence from the northern Tatoosh complex, southern Washington Cascades. *Journal of Volcanology and Geothermal Research*, **54**, 197-220.

Murphy, M. D., Sparks, R. S. J., Barclay, J., Carroll, M. R., Lejeune, A-M., Brewer, T. S., Macdonald, R., Black, S. and Young, S. R., 1998. The role of magma mixing in triggering the current eruption at the Soufriere Hills volcano, Montserrat, West Indies. *Geophysical Research Letters*, **25**, 3433-3436.

Pearce, J. A. and Cann, J. R., 1973. Tectonic setting of basic volcanic rocks determined using trace element analysis. *Earth and Planetary Science Letters*, **19**, 290-300.

Pharaoh, T. C., Webb, P. C., Thorpe, R. S. and Beckinsale, R. D., 1987. Geochemical evidence for the tectonic setting of late Proterozoic volcanic suites in central England, in Geochemistry and Mineralisation of Proterozoic volcanic suites (eds T. C. Pharaoh, R. D. Beckinsale and D. Rickard), *Geological Society of London Special Publication*, **33**, 541-552.

Potter, T. R., 1842. *History and Antiquities of Charnwood Forest* (Appendix on the Geology of the District by J. B. Jukes et al.). Hamilton and Adams, London, 272pp.

Tucker, R. D. and Pharaoh, T. C., 1991. U-Pb zircon ages for Late Precambrian igneous rocks in southern Britain. *Journal of the Geological Society of London*, **148**, 435-443.

Voight, B. and 24 others, 1999. Magma flow instability and cyclic activity at Soufriere Hills Volcano, Montserrat, Brtitish West Indies. *Science*, **283**, 1138-1142.

Watts, W. W., 1947. *Geology of the ancient rocks of Charnwood Forest, Leicestershire*. Leicester Lit. Phil. Society, 160pp.

Williams, H. and McBirney, A. R., 1979. *Volcanology*. Freeman, Cooper & Co., San Francisco, 397pp.

Worssam, B. C. and Old, R. A., 1988. Geology of the country around Coalville. *Memoir of the British Geological Survey*, Sheet 155.

Yarnold, J. C., 1993. Rock-avalanche characteristics in dry climates and the effect of flow into lakes: Insights from mid-Tertiary sedimentary breccias near Artillery Peak, Arizona. *Geological Society of America Bulletin*, **105**, 345-360.

Young, S. R., Sparks, R. S. J., Aspinall, W. P., Lynch, L. L., Miller, A. D., Robertson, R. E. A. and Shepherd, J. B., 1998. Overview of the eruption of Soufriere Hills volcano, Montserrat, 18 July to December, 1997. *Geophysical Research Letters*, **25**(18&19), 3389-3392.

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Fault Reactivation Induced by Mining in the East Midlands

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Abstract: Mining-induced fault reactivation has been observed at several localities throughout the East Midlands, between 1930 and 2000. The generation of new fault scarps has caused widespread damage to structures and land. These scarps are distinct, reach over a metre high and extend for several hundreds of metres at outcrop. In areas of moderate relief, such as on the Permo-Triassic escarpments, natural process of cambering and valley bulging may be exacerbated by mining subsidence. Recent field observations suggest that some faults may undergo renewed phases of reactivation, several years after mining has been abandoned, probably due to minewater rebound, although this is difficult to prove at some sites. Some of the engineering problems and environmental geohazards associated with fault reactivation are outlined with reference to case examples.

Ground movements due to mining subsidence can be normally predicted with a reasonable degree of accuracy and precision (Whittaker and Reddish, 1989). Faults within regions undergoing subsidence are susceptible to reactivation, and their renewed displacements disrupt the predicted profiles of ground movement. At several localities in the East Midlands, fault reactivation has results in the formation of distinct, and often extensive, fault scarps up to 1.5m high across the ground surface. Mining subsidence, with and without fault reactivation, has caused widespread damage to land, property and structures. Furthermore, some faults may provide natural pathways for groundwater discharges and minegas emission.

In recent years inadequate attention has been paid to the effects of geological processes in the design and construction of many buildings and structures (McCann *et al.*, 1999; Culshaw *et al.*, 2000). This has resulted in spiralling costs of claims based on "unforeseen ground conditions". Fault reactivation is just one of many causes of adverse ground conditions in Britain, although it is poorly understood by many engineers and non-technical specialists. This paper highlights some of the problems caused by fault reactivation in the East Midlands that may be significant for many geologists, engineers, builders, surveyors, planners, insurers and conveyance lawyers.

Fault Reactivation in the East Midlands

Fault scarps caused by mining subsidence are often described by subsidence engineers, as steps in the subsidence profile or 'break-lines' along the ground surface (Fig. 1). In the East Midlands, these have damaged civil-engineered structures, residential houses, industrial premises, roads, motorways and railways. Movement along faults has also effected underground utilities such as gas and water mains,

Figure 1. Reactivation of a fault generated a 0.3m high fault scarp and caused severe damage to a 5m high brick wall at Eastwood Hall. The date of reactivation is not known, but was probably in the 1960s. This section of wall has been demolished, but evidence of further fault reactivation was visible on an opposing wall in May 2000.

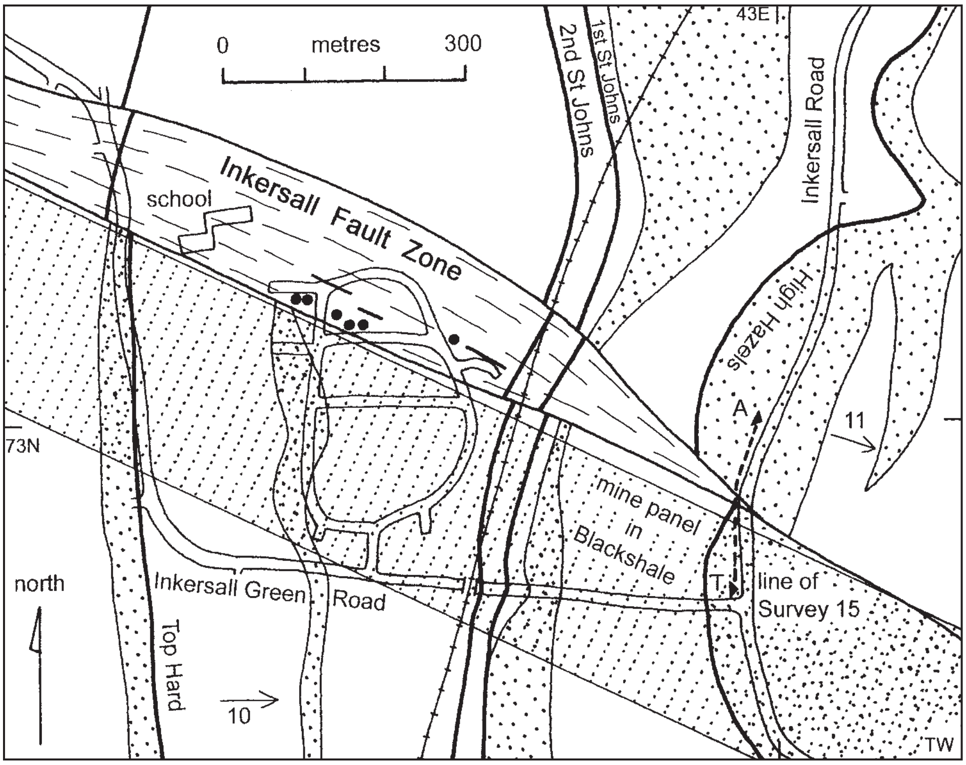

Figure 2. Geological map of the Inkersall Fault at Inkersall Green. Coal seams are named, sandstone outcrops are stippled, and the rest of the outcrop is mainly mudstone of the Coal Measures. The outer limits of the fault zone are as recorded on the BGS map; the short fault lines marked within the zone have reactivated to create scarps. Solid circles indicate the sites of buildings that have been demolished.

sewers, drains and communication cables. Agricultural land has been disturbed due to the localised alteration of the gradient and flooding. Only recently have the factors that control the mechanisms of mining-induced fault reactivation been identified, following commissioned research into the influence of faulting on mining subsidence (Donnelly, 1994). As a part of this research, several case histories of mining-induced fault reactivation were investigated in the East Midlands (at some sites noted below, specific details and locations have been omitted, due to their current sensitivity and confidentiality).

Inkersall Fault, Chesterfield

This fault crops out in the Middle Coal Measures, near to the villages of Staveley and Inkersall, 6km east of Chesterfield. The fault zone is bounded by two sub-parallel fractures separated by a distance of a few hundred metres (Fig. 2). It is a steep normal fault with an apparent sinistral component of slip, dipping at 74°NE, with a throw of 30-50m. At least six coal seams have been extracted close to, and on both sides of, the Inkersall Fault.

The earliest records of fault reactivation were during the working of the Deep Hard seam in the 1950s, at depths of around 28m below Inkersall. Further phases of reactivation occurred in 1985, during the working of the Piper seam, at about 300m depth, from Markham colliery. This created surface movements that caused severe damage to property in the Inkersall Green housing estate, and generated fault scarps (Fig. 3) that were locally over 1.5m high. Eight houses (Fig. 2) were severely

Figure 3. Reactivation of the Inkersall Fault in the 1980s, caused widespread damage at the northern end of the Inkersall Green housing estate; this small graben feature formed across a road over a subsidiary fault within the Inkersall fault zone.

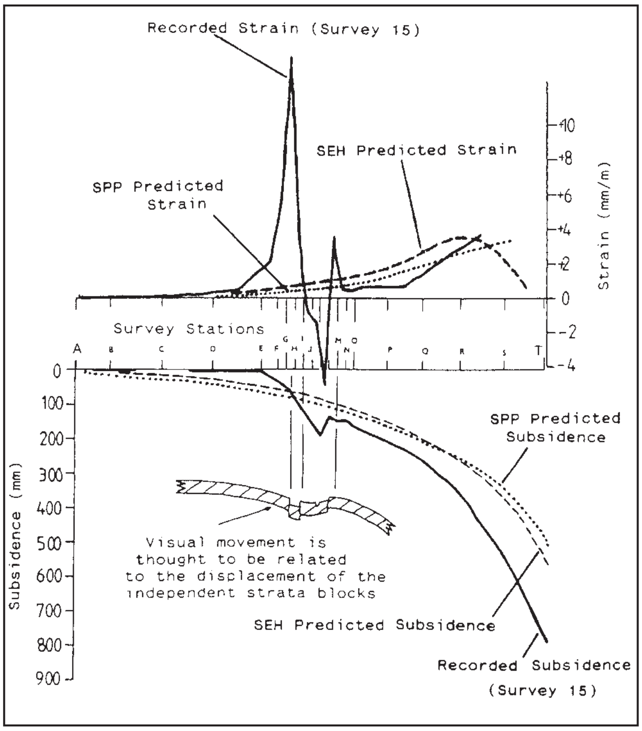

Figure 4. Profiles of subsidence and ground strain measured along survey line #15 across the Inkersall Fault (see Figure 2), showing reactivation in 1988; the broken lines indicate predicted profiles that took no account of the fault movement (after Phillips and Hellewell, 1994).

damaged by fault movements and were subsequently demolished; since the mining has ceased under Inkersall, new houses have been placed on some of these sites. The school was also severely affected and there was extensive damage to roads, walls, pavements, and utilities. Yet more houses on the fault zone were badly damaged or tilted and remained unoccupied for several years. Houses outside the fault zone suffered only the modest damage, as was normal for mining subsidence on unfaulted ground.

Further reactivation of the fault was monitored from August 1987 to December 1988, during the working of the Blackshale seam at a depth of 405m (Phillips and Hellewell, 1994). Observational data suggested that the strong sandstones fractured at outcrop, causing widespread damage due to the cantilevering effect of the individual blocks (Fig. 4). This explained reverse stepping, that is associated with cantilever movements of sandstone beds at outcrop. Residents described loud bangs and rumblings from deep underground; some assumed that these were blasting in the mine, but they originated from collapses in the mine and from disturbances in the faulted sandstones.

In 1991, following reports of further movements along the fault and renewed structural damage to the school and houses in Inkersall Green (Fig. 5), two monitoring lines were established. These were set across the fault along Inkersall Road and Inkersall Green Road and were surveyed regularly from January 1992 to July 1993 (Donnelly, 1994). The new data confirmed the gradual demise of fault reactivation.

Sheepbridge Lane Fault, Mansfield

This fault is a major geological structure bounding the southern limb of the Hardsoft-Mansfield Anticline, aligned roughly NW-SE. The fault crops out in Triassic sandstones, which overlie the Coal Measures and are comparatively undisturbed, dipping gently to the east. Where the fault crosses Roebuck Drive a fault scarp, in the form of a gentle flexure, developed across the road surface during the working of the Deep Soft seam in 1984. The scarp was about 100m north of the inferred outcrop position on BGS maps. The structural damage was slight to moderate on the subsidence classification scheme (NCB, 1975), and was restricted to the road surface, pavement, kerbstones and a few houses.

At least five coal seams had been previously extracted in the footwall region of this fault since the early 1930s. Some of the workings, including those in the Top Hard seam, extracted coal right up to the fault, but there were no reports of fault reactivation until 1984. This does not necessarily imply that reactivation did not occur before this date, as maybe it was not recognised. In 1991, following observations of fault movement and reports of slight structural damage, two precise levelling lines were established along Roebuck Drive and Nottingham Road (A60) during the working of the Deep Hard seam at a depth of around 460m (Donnelly, 1994).

Figure 5. A scarp within the Inkersall fault zone during the early 1990s phase of reactivation, in the back garden of a house at Inkersall Green.

These were surveyed on a regular basis until August 1993, but did not record movement along the fault. Anticipating that reactivation may occur, specifically designed, narrow longwall panels were used to extract the coal; this reduced the effects of subsidence and fault reactivation.

Springswood Street, Temple Normanton

On 29th April 1966, a distinct scarp developed across Springswood Street and caused severe and extensive damage to several terraced houses. Local newspaper reports described the scarp and claimed that it appeared during the working of the Clay Cross Soft seam, 250m below the village, from workings at Williamthorpe Colliery (now closed). One newspaper report stated that "*local gas mains fractured and four houses were demolished piece by piece since they were too dangerous to be bulldozed*". The scarp coincided with the outcrop position of the High Hazles seam and may have been generated by translational bedding plane shear and not by the reactivation of a fault. Shear movements along bedding planes are not uncommon during mining subsidence and have been documented elsewhere in Britain and in the Ukraine (Donnelly and Reddish, 1993).

Vale Road, Mansfield Woodhouse

In 1976, a fault scarp 1m high developed across Vale Road (Fig. 6), causing severe damage to the road, pavements, walls and neighbouring houses. Photographic evidence of repairs to the road surfaces implies that several phases of reactivation may have occurred. This is not uncommon, as faults are capable of multiple phases of reactivation, during mining of three or more seams, separated by periods of relative stability. Although fault reactivation may continue for weeks or years after 'normal' mining subsidence has ceased, movements along faults do also eventually cease.

Shirburne Avenue, Mansfield

In 1992, a house was moderately damaged during mining subsidence after it had been built across a contact between the Magnesian Limestone and the Coal Measures. The structural damage was caused by dilation and translational shear along the lithological contact, during mining subsidence. The position of the contact was proved in 1992 by a seismic survey and an exploratory trench.

Papplewick

The reactivation of a fault generated a scarp that damaged a private house so badly that it was subsequently demolished. The BGS map shows a fault at outcrop in the Lower Magnesian Limestone and Upper Permian Marl at the site. The date of reactivation is not known, but it was probably during working of the Deep Soft seam in 1968, the Blackshale seam in 1971, or both.

Aspley, Nottingham

Reactivation of the 15 Yards Fault was noted by Lee (1965), when the Deep Soft and Deep Hard seams were mined from beneath its western side. Photographs show damage to at least six houses on Newlyn Drive and the ring road, prior to their demolition. There is anecdotal evidence for later reactivation of this fault (Donnelly, 1994), and it is still marked by a low ramp on the ring road.

Figure 6. Reactivation of a fault in 1976, generated a scarp 0.5m high that caused moderate damage to Vale Road, Mansfield.

Gulls at Pleasley Vale, Mansfield

At Pleasley, valley bulging occurs in mudstones on the lower and middle valley slopes causing cambering of the overlying sandstones and limestones that form a strong caprock on the valley margins. This has created the many gulls – caprock ground fissures that lie parallel to the valley sides. Where these have been undermined by deep coal workings, the gulls have dilated in the tension zones induced by subsidence. These fissures are generally filled with rock fallen from their sidewalls or are bridged by superficial deposits, soil and turf. Gulls were exposed in the cuttings of the Pleasley by-pass, but are now less clearly visible in the weathered faces. Where effectively masked by the soil cover on level ground, gulls are particularly hazardous in areas that are undermined.

Belvoir Street, Hucknall

Individual houses in the two long terraces down Belvoir Street were severely damaged when they were undermined in 1955 (Fig. 7). The site is on the outcrop of the Magnesian Limestone, and the damaged houses appear to lie above a few major fissures. The houses on each side along the terraces suffered only minimal movements, as they stood on stable blocks of limestone. The damaged houses had to be completely rebuilt, but subsequent mining of deeper seams caused renewed movement and repeated damage on a lesser scale to the same houses. Mining has now ceased and there has been no recent movement.

Figure 7. Damage to a terraced house in Belvoir Street, Hucknall, in 1955. The house has since been rebuilt.

The A610 bypass, Ripley

In 1992, a graben about 60m long and 1.5m wide, was accompanied by subsidiary scarps, compression humps and en-echelon fissures across the roundabout on the A610 outside the police headquarters. The date when the scarps first appeared is not known, but their growth has caused visible damage to the road surfaces, roundabout, pavement, grass verges and fields almost continuously until the present day. The main scarp is currently marked by a low east-facing step in the road surface (Fig. 8), whose frequent repairs cause temporary traffic delays. There is no current mining beneath the site, and the continuing deformation of the ground is not fully understood.

Boothorpe Fault, Woodville and Swadlincote

The Boothorpe fault marks the northeastern boundary of the South Derbyshire coalfield. In 1995, the reactivation of the fault produced a west-facing fault scarp 0.2m high and over 50m long. This caused moderate damage to road surfaces, drains, brickwork, windows, doorframes, sills, kerbstones, and footpaths, but the scarp was less conspicuous in grass verges. Houses close to the fault were skewed and tilted, and a garage door directly over the trace of the fault was severely buckled. Gaps in rows of houses along the fault outcrop are thought to represent the sites of previous phases of fault reactivation that resulted in damage and subsequent demolition. En-echelon fissures were observed sub-parallel to the fault scarp, in asphalt and concrete driveways. Evidence for the reactivation of this fault was limited to field observation and geological mapping, and appraisal of mining records are required to verify this interpretation.

Burton Road and Ashby Heights, Woodville

In 1963, 1992 and 1994, reports from local geotechnical consultants, provided information on the reactivation of a fault, which was claimed to be the Boothorpe Fault, where one phase of movement caused the failure of an embankment in the rear of a house on Burton Road. This created a scarp, that was matched with further movements along the fault in the Ashby Heights area of Norris Hill. Subsequent investigations by the BGS and others confirmed that the scarp did represent mining-induced fault reactivation, though this was not the Boothorpe Fault (which lies 400-500m southwest of the Burton Road site). However, other investigators have disputed whether the failure of the embankment was caused by the reactivation of a fault.

Moira Fault, Overseal

The reactivation of this fault, along the southwestern margin of the South Derbyshire coalfield, was first documented in 1939, on wartime coalfield reconnaissance field maps. The movement was interpreted as being induced by differential subsidence along the Moira Fault, caused by underground coal mining along the eastern side, in the footwall. A fault scarp was also noted on a 1970 BGS field map, along the outcrop of the Moira Fault. Unconfirmed reports of further movements along the fault were given in 1991 and 1995.

Copperas Road, Stanton, Burton

In 1985, several faults experienced mining-induced reactivation in Stanton, over the western tip of the South Derbyshire coalfield. The faults were proved in underground workings in the Main, Eureka and Stanhope seams, but there are no recorded details of the extent and intensity of damage caused by fault reactivation.

Groundwater rebound at Swannington

In 1996, field observations and groundwater monitoring around Swannington, Leicestershire, provided evidence of ground deformation as a consequence of minewater rebound (Smith and Colls, 1996). Two scarps were observed across a field, 250m from the Church Hill pumping station (now demolished). These were sub-parallel, 0.7m high, trending NW-SE, over a length of 30-40m, in weathered clays of the Coal Measures. An amateur archaeologist, living nearby, reported that the scarps developed over an 18-month period. The upper scarp was more recent, but the lower scarp was more distinct and caused damage to a field drain by shearing. Comparable cases of movement along faults in the absence of mining, have been reported in other British coalfields. Though the processes are not fully understood, it appears that the faults are reactivated by the rising groundwater pressures that follow the cessation of mine drainage (Donnelly, 2000).

Engineering on faulted ground

The majority of faults in the former and current mined regions of the East Midlands are stable. However, under certain circumstances renewed ground movement with or without potentially detrimental side-effects can occur. Faults may enhance the permeability of a rock mass between mined seams and the ground surface, creating pathways for groundwater, minewater and mine gas discharges into the surface environment. The potentially explosive, noxious and asphixiating gases include methane (firedamp), carbon monoxide (whitedamp), hydrogen sulphide (stinkdamp), ‘stythe’ (blackdamp – air that is depleted of oxygen and enriched with carbon dioxide) and radon. Rising groundwater along faults may also cause non-mining-related subsidence due to the washing out of clay or silt fines from granular materials. Aggressive waters may cause chemical attack of buried concrete structures and foundation piles. Fault zones that contain weak gouge infilling may create ground with reduced

Figure 8. The latest in a series of fault reactivation phases, from 1991 to 2000, causing moderate to severe damage to the A610 bypass at Ripley.

Figure 9. A fault scarp across a road in a housing estate at Inkersall, near Chesterfield, has reactivated as successive coal seams have been mined from beneath, causing repeated damage to the road and adjacent houses.

bearing capacity that can cause differential settlement to structures.

Following partial or complete abandonment of a coalfield, minewater pumping stations, necessary to keep modern active workings from flooding, are usually shut down. The environmental consequences of mine closure in urban Britain, in addition to the social and economic problems, are primarily related to the recovery of groundwater levels on termination of the pumping and consequent flooding of the abandoned mine workings. Should water levels rise to the ground surface, discharges may cause pollution and contamination of surface watercourses and aquifer water supplies (Dumpleton and Glover, 1989; Younger, 1994). Minewater rebound may increase porewater pressures within faults, thereby reducing normal stress across the fault and consequently reducing shear strength - to a level that reactivation may occur. Under these conditions, faults may be susceptible to reactivation in the absence of current mining (Smith and Colls, 1996; Donnelly, 2000). This is not expected to be widespread across the East Midlands, but may occur at sites on major faults that have a history of reactivation or have been previously undermined.

The hazards of fault reactivation

The purpose of this paper has been to draw attention to some effects of fault reactivation in the East Midlands, as a consequence of underground coal mining. These faults have generated distinct and occasionally extensive scarps across the ground surface, and have caused widespread damage to structures, utilities and land (Fig. 9). The scarps tend to be temporary features of the landscape, and are soon destroyed by land redevelopment, necessary road repairs, or ploughing of fields. It is necessary to record the precise location and reactivation history of these faults, since they may have a significant bearing on future land use and civil engineering.

Where faults crop out in strong, well-jointed, competent limestone or sandstones, open fissures may be created by dilation of the fault plane. This is most common on sloping ground that also has gulls due to past cambering. Both fissures and gulls are commonly not visible where they are wholly or partly filled by debris and spanned by the soil cover.

Topographic scarps may be generated during mining subsidence in the absence of faults, while sharing the morphological characteristics of a fault scarp. These occur due to translational shear along bedding planes; they occur most frequently at bedding interfaces between strong sandstone or limestone and weak mudstone, and by differential displacements along coal seam contacts with mudstone.

There is often a tendency in mining regions to attribute the appearance of ground surface scarps to fault reactivation, merely due to the known existence of local mining. However, it is significant that topographic scarps may also be generated by natural processes such as cambering, or by other events such as the collapse of buried drains. Each situation requires detailed assessment of the geology and mining history. Reactivated faults are frequently the source of disputes, due to the damage that they may cause, and can result in legal claims for compensation. Unfortunately, due to perceived sensitivity, most of the cases of fault reactivation are known only to those who have carried out subsidence-related investigations. There is no public record of fault reactivation activity (Donnelly, 1996), and consequently some areas in the old coalfields are undergoing regeneration and redevelopment on ground that has a history of fault movements. Provided that no further phases of reactivation, gas emissions or groundwater discharges occur, this should not present any problems, but total stability can rarely be guaranteed.

Residual movements along faults in the absence of mining have been reported at some locations. These are not all fully understood, and some cases may be due to the deterioration of the road or structure itself. In certain circumstances, for instance during minewater rebound following the cessation of pumping, renewed fault reactivation may be possible, but this can be difficult to prove.

The slight risk of fault reactivation should not blight land or property in the East Midlands, since most faults are now stable. Engineering geologists should familiarise themselves with the potential problems associated with faulted ground, and should identify these for engineers, builders, planners, insurers and conveyance lawyers who are concerned with both urban and greenfield sites where previous mining may have taken place.

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References

Culshaw, M. G., McCann, D. M. and Donnelly, L. J., 2000. Impacts of abandoned mineworkings on aspects of urban development. *The Legacy of Mineral Extraction*. Inst. Min. Mech. Eng. Conference, Newcastle-upon-Tyne.

Donnelly, L. J., 1994. *Predicting the Reactivation of Faults and Rock Mass Discontinuities During Mineral Exploitation, Mining Subsidence and Geotechnical Engineering*. PhD thesis, University of Nottingham.

Donnelly, L. J., 1996. UK national fault reactivation register: a proposal. *British Geological Survey Note* PN/96/2.

Donnelly, L. J., 2000. The Reactivation of Geological Faults during Mining Subsidence from 1859 to 2000 and beyond. *The Legacy of Mineral Extraction*. Inst. Min. Mech. Eng, Conference, Newcastle-upon-Tyne.

Donnelly, L. J. and Reddish, D. J., 1993. The development of surface steps during mining subsidence not due to fault reactivation. *Engineering Geology*, **36**, 243-255.

Dumpleton, S. and Glover, B. W., 1995. The impact of colliery closures on water resources, with particular regard to NRA Seven-Trent Region. *British Geological Survey Technical Report* WD/95/40.

Lee. A. J., 1965.*The effects of faulting on mining subsidence*. MSc thesis, University of Nottingham.

McCann, D. M., Culshaw, M. G. and Donnelly, L. J., 1999. Impact of geological processes on the stability of structures. *Structural Faults and Repairs 99*. Conference at The Commonwealth Institute, Kensington.

NCB, 1975. *Subsidence Engineer's Handbook*. National Coal Board, London.

Phillips, K. A. S. and Hellewell, E. G., 1994. Three-dimensional ground movements in the vicinity of a mining activated geological fault. *Quart. Journ. Eng. Geol.*, **27**, 7-14.

Smith J. A. and Colls, J. J., 1996. Groundwater rebound in the Leicestershire Coalfield. *Journal of the Chartered Institution of Water and Environmental Management*, **10**, 280-289.

Younger, P. L., 1994. Minewater pollution: the revenge of Old King Coal, *Geoscientist*, **4** (5), 6-7.

Whittaker, B. N. and Reddish, D. J., 1989. *Subsidence: Occurrence, Prediction and Control.* Elsevier, 528pp.

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A large Rhomaleosaurid Pliosaur from the Upper Lias of Rutland

Richard Forrest

Abstract: The fragmentary remains of a very large rhomaleosaurid pliosaur were retrieved during building works at Barnsdale Hall, Rutland. The limited material prevents clear identification at specific level, though on the basis of similarities of ratios of dimensions it shows closer affinity to Rhomaleosaurus arcuatus and R.victor than to R.cramptoni. Although scaling up from such fragmentary material is unreliable, the estimated length of this animal at 7.5 to 8 metres makes it possibly the largest Rhomaleosaurid pliosaur described to date.

The fossil material

The bones were excavated in 1988 by Mr. Roy Draycott during construction of a retaining wall at Barnsdale Hall, east of Rutland Water, in the county of the same name. An outer whorl of the ammonite *Hildoceras bifrons* was found in association with the bones. It can therefore be placed with confidence in the *bifrons* Zone of the Upper Lias (Lower Jurassic, Toarcian, Whitbian). It is probable that much more extensive remains of the animal were present at the time. No further investigation is possible in the foreseeable future, as it would involve extensive and expensive demolition works.

The material (LEICT G2.1988.1 and .2) consists of a fragment comprising the proximal third of a right femur, and a complete right tibia.

The femoral fragment (Fig. 1) measures 225 mm long and approximately 150 mm wide. At the broken end the shaft is oval in section, 148 mm wide and 96 mm deep. The head is 153 mm broad and 160 mm deep. Orientation can be determined by rugosities from ridges for muscle attachment on the posterior side and the ventral surface. A deep hole in the posterior muscle attachment presumably marks where a ligament was connected to the bone. There is slight taphonomic crushing around the trochanter. The surface is encrusted in places with a pyritised deposit, which shows traces of tracks left by scavengers post-mortem. The internal structure of the bone is preserved, and the broken end shows clearly an outer rim of perichondral bone about 12 mm thick, and the endochondral interior.

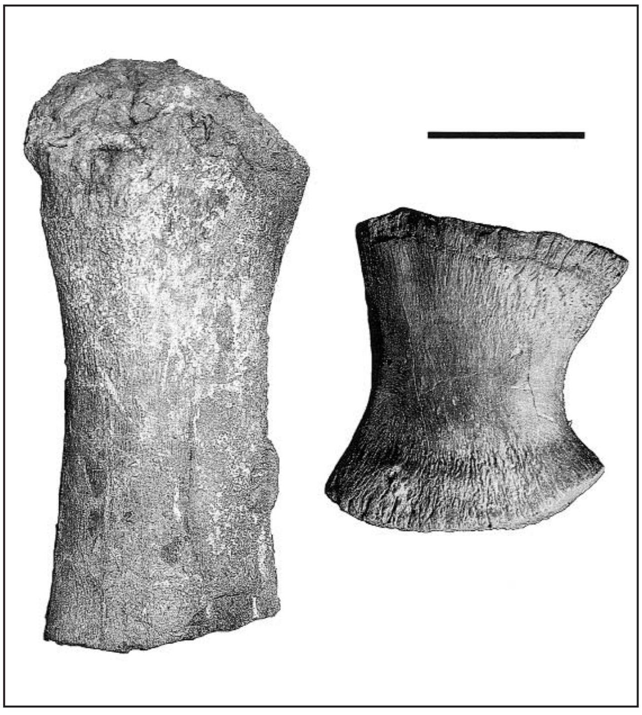

Figure 1. *Rhomaleosaurus. sp.*: left, the right femur (LEICT G2.1988.1), 325mm long; right, the right tibia (LEICT G2.1988.2), 200mm long. The scale bar is 100mm long.

The tibia (Fig. 1) is roughly hourglass shaped, measuring 200 mm long and 180 mm wide, waisting to 120 mm in the middle. Both ends are curved in plan, the distal end rather more so than the proximal. The curvature of the posterior face is greater than that of the anterior. In section it is lens-shaped, the curvature of the ventral face being less than that of the dorsal. It shows some localised crushing at the proximal end which may be due to damage by predation, though is more likely the result of taphonomic processes. The distal end is slightly crushed by taphonomic processes. The surface is clean and shows no traces of post-mortem scavenging. Three foramina on the dorsal surface show a pattern of small indentations around the rim which probably mark the position of small blood vessels. A small, narrow penetration at the distal end of the ventral surface and an associated small raised area of bone may be damage from predation or post-mortem scavengers.

Identification

Diagnosis on the basis of such limited material is unreliable. On the basis simply of size and horizon, the material is probably attributable to the pliosaurian genus *Rhomaleosaurus*. The general morphology of the material supports this, in particular the tibia, which is similar in shape to those of *R. cramptoni* (Carte and Baily, 1863) and *R. victor* (Fraas, 1910). Published accounts of pliosaur limb elements are rare, and limited mainly to Callovian and later forms. It is possible that their

		Rhomlaeosaurus sp.	*R.arcuatus*	*R.cramptoni*	*Rhomaleosaurus sp. c.f. R.arcuatus*	*R.victor*
		LEICT G2.1988.2	LEICT G221.1851	BMNH R. 34	WARMB G10875	SMNK 3.7.1
		Measurement by author from specimen	Measurement by author from specimen	Carte and Baily, 1863	measurements by A.R.I Cruickshank and M.A.Taylor	Fraas 1910
H3	Proximal width of femur	153	115	182	105	90
H4	Narrowest portion of femur	120	70	131	70	112
H5	From posterior extreme of widest part of proximal end of femur to centre of ligament insertion mark	190	115	163	100	54
H6	Length of tibia	200	145	165	110	120
H7	Distal breadth of tibia	180	100	127	60	115
H8	Proximal breadth of tibia	180	130	152	107	106
H9	Narrowest portion of tibia	120	87	136	74	84

Table 1. Measured dimensions of *Rhomaleosaurus*.

shape owes more to ontogenetic processes than true taxonomic differences.

As an exercise in the extraction of information from limited material, a metrical approach was taken. Dimensions were collected for five specimens of the genus *Rhomaleosaurus*, from published accounts (Carte and Baily, 1863. Fraas, 1910), unpublished measurements by Arthur Cruickshank and Michael A. Taylor, measurements by the author from the material, and measurements scaled from photographs (Table 1). Seven dimensions can be measured on this and the four other specimens and a data matrix was constructed to show the relative proportion of each to all of the others. The proportion of the logarithm of each of the ratios in the matrix against that for the Barnsdale specimen was calculated. The average of all the resultant ratios for each specimen can therefore be taken as a measure of the 'morphological difference' between them (Table 2). The results were plotted against the averaged length of all seven dimensions of each specimen (Figure 2). This shows that the Barnsdale specimen is morphologically closer to LEICT G221.1851 (*R.. arcuatus* [Cruickshank, pers. comm., formerly *R.. megacephalus*]) and SMNK 3.7.1 (*R.. victor*) than to BMNH R.34 and WARMS R10875 (*R. cramptoni*).

This result should not be interpreted as demonstrating a taxonomic relationship. Ontogenetic changes in plesiosaurs are not well known, and the morphological closeness may owe more to similarity in developmental stage than to taxonomic relationship. Until more is known of pliosaurian ontogeny, no firm conclusions can be drawn from such limited data.

Overall length is known for three specimens, Rhomaleosaurus arcuatus LEICT G221.1851 (The 'Barrow Kipper') (Taylor and Cruickshank, 1989. Cruickshank, 1994a, Cruickshank, 1994b), R. cramptoni type specimen (Cast BMNH R34) (Carte and Baily, 1863), and R.. victor (SMNK 3.7.1). Taking the ratios of measurable dimensions to the overall length and extrapolating from the tibia of the Barnsdale specimen gives an overall length of 7.76m, 8.26m and 6.03m for the three specimens respectively. *R. victor* is a much smaller animal than the other two, and the lower estimated length is attributable to morphological differences due to size. The best estimate for the overall length of the animal

Rhomaleosaurus sp LEICT G2.1988								
		H3	H4	H5	H6	H7	H8	H9
		153	120	190	200	180	180	120
H3	153	0					average	0
H4	120	0	0				sum	0
H5	190	0	0	0				
H6	200	0	0	0	0			
H7	180	0	0	0	0	0		
H8	180	0	0	0	0	0	0	
H9	120	0	0	0	0	0	0	0

Rhomaleosaurus arcuatus LEICT G221.1851 (Barrow Kipper)								
		H3	H4	H5	H6	H7	H8	H9
		115	70	115	145	100	130	87
H3	115						average	0.0096
H4	70	-0.1101					sum	0.2026
H5	115	-0.0941	0.0160					
H6	145	-0.0157	0.0944	0.0784				
H7	100	-0.1313	-0.0212	-0.0372	-0.1156			
H8	130	-0.0173	0.0928	0.0767	-0.0017	0.1139		
H9	87	-0.0157	0.0944	0.0784	0.0000	0.1156	0.0017	

Rhomaleosaurus cramptoni BMNH R.34 (Cast of type)								
		H3	H4	H5	H6	H7	H8	H9
		182	131	163	165	127	152	136
H3	182						average	-0.0353
H4	131	-0.0373					sum	-0.7420
H5	163	-0.1419	-0.1047					
H6	165	-0.1589	-0.1216	-0.0170				
H7	127	-0.2268	-0.1896	-0.0849	-0.0679			
H8	152	-0.1488	-0.1115	-0.0069	0.0101	0.0780		
H9	136	-0.0210	0.0163	0.1209	0.1379	0.2058	0.1278	

Rhomlaeosaurus sp., c.f R.arcuatus WARMS R10875								
		H3	H4	H5	H6	H7	H8	H9
		105	70	100	110	60	107	74
H3	105						average	-0.0306
H4	70	-0.0706					sum	-0.6426
H5	100	-0.1153	-0.0447					
H6	110	-0.0961	-0.0256	0.0191				
H7	60	-0.3136	-0.2430	-0.1984	-0.2175			
H8	107	-0.0624	0.0082	0.0529	0.0337	0.2512		
H9	74	-0.0464	0.0241	0.0688	0.0497	0.2672	0.0159	

Rhomlaeosaurus victor SMNK 3.7.1								
		H3	H4	H5	H6	H7	H8	H9
		90	112	54	120	115	106	84
H3	90						average	0.0170
H4	112	0.2005					sum	0.3568
H5	54	-0.3159	-0.5164					
H6	120	0.0086	-0.1919	0.3245				
H7	115	0.0359	-0.1646	0.3518	0.0273			
H8	106	0.0005	-0.2000	0.3164	-0.0081	-0.0354		
H9	84	0.0755	-0.1249	0.3915	0.0669	0.0397	0.0751	

Table 2. Log of differences in ratios of dimensions of the pliosaur specimens.

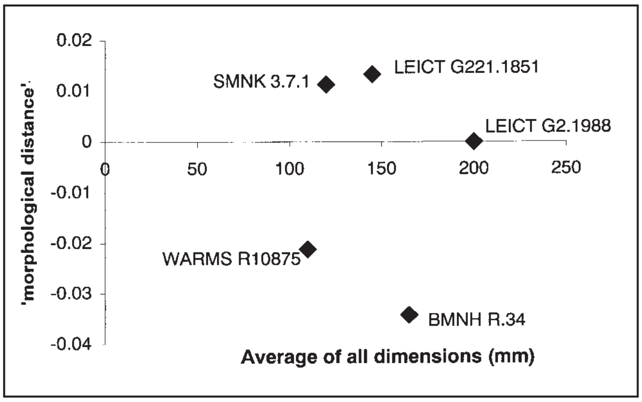

Figure 2. Compaison of sizes and morphological differences of the pliosaur specimens.

from which LEICT G2.1988 came is between 7.5m and 8.0m.

A very rough estimate of the weight of this and other specimens of the genus *Rhomaleosaurus* was made by interpolating between the volumes of plastic models *Liopleurodon* and an elasmosaur. The assumptions were made that the morphology of *Rhomaleosaurus* is more or less mid-way between the two (the of *Rhomaleosaurus* neck is long, but the head and body are large) and the specific gravity is close to that of water - a reasonable assumption for a marine animal. This methodology allows estimation of the animals' weights (Table 3). It is worth noting that the Barnsdale specimen is half as heavy again as the type of R. *cramptoni*, and over three times the weight of the Barrow specimen of R. arcuatus.

Discussion

Very large pliosaurs are known from several Jurassic and Cretaceous marine reptile faunas. *Liopleurodon and Simolestes* from the Oxford Clay (Andrews, 1910-13) achieved estimated lengths in excess of 10 m. Fragmentary remains of a very large Callovian pliosaur possibly as long as 17 m were reported by McHenry *et. al.* (1996). Tarlo (1959, 1960) proposed the genus *Stretosaurus* for a large pliosaur from the Kimmeridge Clay (length approximately 15 m), though this material is now ascribed to the genus *Liopleurodon* (Halstead, 1989). *Brachauchenius* (Carpenter, 1996) from the Late Middle Cretaceous of North America reached a comparable size. *Kronosaurus* (Longman, 1924) from the Middle Cretaceous of Australia is the best known of the large pliosaurs. More recent finds from Australia (McHenry, pers. comm.) and Columbia (Hampe, 1992) have shown that the well-known mounted specimen in the Harvard Museum of Natural History (Romer, 1959) is an inaccurate reconstruction in that the body was relatively shorter, though it remains a very large animal.

R. victor (SMNK 3.7.1)	700kg
R. arcuatus (LEICT G211.1851)	2400kg
R. cramptoni (BMNH R. 34)	5600kg
Rhomaleosaurus sp. (LEICT G2.1988)	8000kg

Table 3. Estimated weights of pliosaur species.

A series of very large reptilian marine predators is known from the Triassic to the Upper Cretaceous. Triassic ichthyosaurs, such as the Carnian *Shonisaurus* (Camp, 1976. McGowan and Motani, 1999) reached lengths in excess of 15m. A recently found ichthyosaur from the Upper Triassic of British Columbia (Tyrrell Museum, 1999) is far larger than any previously recorded marine reptile, with a skull length of 5.5 m suggesting an overall length of over 23 m. Specimens of the Liassic *Temnodontosaurus* indicate a body length of about 10m, and there are fragmentary remains of an even larger ichthyosaur from the same stratigraphic level (McGowan, 1997). Pliosaurs seem to have taken on the 'top predator' role for much of the Jurassic and Lower Cretaceous, being replaced in the Upper Cretaceous by the mosasaurs, such as the 17m *Mosasaurus hoffmanni* and the 15m *Hainosaurus bernardi* (Lingham-Soliar, 1995 and 1992).

There is no evidence that pliosaurs possessed any form of echo-location, such as that of modern cetaceans, and it is likely that they located prey by 'smell' (Cruickshank et al., 1991) and used their good binocular vision at close quarters. Taylor (1992) showed that the skull of *Rhomaleosaurus zetlandicus* was 'designed' to resist strong torsional forces, and was well adapted for dismembering large prey by rotational feeding, a common strategy in large modern crocodiles. Although the ichthyosaurs were faster swimmers than the plesiosaurs (Massare, 1988), it is possible that the latter were able to replace the ichthyosaurs in their top predator role by virtue of a more effective sensory system. An analysis of feeding strategies used by pliosaurs from the Oxford Clay biota is given by Martill et al. (1994). Predation by large pliosaurs on smaller, long-necked forms is documented from the Cretaceous of Australia (Thulborn and Turner, 1993).

The disappearance of large pliosaurs in the Turonian, and the appearance of mosasaurs in the Cenomanian (Cruickshank and Long, 1997) may be due to superior predation strategies in mosasaurs, though there is no evidence of this. Williston (1897) suggested from the evidence of re-healed broken bones that mosasaurs 'exhibited an aggressive disposition beyond that of normal predatory behaviour'. Such evidence is by no means conclusive and in any case there can be little doubt from documented pliosaur bite marks (Thulborn and Turner, 1993; Clarke and Etches, 1991) that pliosaurs were themselves highly aggressive. Unpublished research by the author has found in a sample of propodials of the genus *Cryptoclidus* that 75% show bite marks probably attributable to pliosaurs. Any adaptive advantage of mosasaurs has left no fossil record.

The Barnsdale specimen approaches in size the largest Callovian and Kimmeridgian pliosaurs, and dates from the period of transition from the ichthyosaurs to the pliosaurs as top marine predators between the Pliensbachian and the Toarcian. The specimen suggests that it was the development of large size in pliosaurs, and not any environmental disturbance that enabled them to gradually replace the large ichthyosaurs.

Acknowledgements

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Abbreviations

BMNH -Natural History Museum, London.
LEICT - New Walk Museum, Leicester.
WARMS - Warwickshire Museum, Warwick.
SMNK - Staatliches Museum für Naturkunde,
Löwentor Museum, Stuttgart, Germany.

References

Andrews, C.A., 1910-13. *A descriptive catalogue of the marine reptiles of the Oxford Clay, Parts I and II.* British Museum Publication.

Camp, C.L., 1976. Vorläufige Mittleilung über grosse Ichthyosaurier and der oberen Trias von Nevada. *Sitzunsbereiche der Österreichisschen Akademie der Wissenschaften.* Mathematisch-Naturwissenschaftliche Klasse, Abteilung 1 185, 125-143.

Carpenter, K., 1996. A review of the short-necked plesiosaurs from the Cretaceous of the Western Interior, North America. *Neues Jahrbuch Geologie und Palaontologie, Abandlung.*, **201**, 259-287.

Carte, A. and Baily, W.H., 1863. Description of a new species of Plesiosaurus from the Upper Lias near Whitby. *Journal of the Royal Dublin Society*, **4**, 160-170.

Clarke, J. B. and Etches, S., 1991. Predation amongst Jurassic marine reptiles. *Proc. Dorset Nat. Hist. and Archaeol. Soc.*, **113**, 202-205.

Cruickshank, A. R. I., Small, P. G. and Taylor, M. A., 1991. Dorsal nostrils and hydrodynamically driven underwater olfaction in plesiosaurs. *Nature*, 352.

Cruickshank, A.R.I., 1994a. Cranial anatomy of the Lower Jurassic pliosaur Rhomaleosaurus megacephalus (Stuchbury) (Reptilia: Plesiosauria). *Phil.Trans. R. Soc. Lond. B*, 343, 247-260

Cruickshank, A.R.I., 1994b. The cranial anatomy of Rhomaleosaurus thorntoni Andrews (Reptilia, Plesiosauria), *Bull. Nat. Hist. Mus. Lond.(Geol)*, **52** (2), 109-114

Cruickshank, A.R.I. and Long, J. A., 1997. A new species of pliosaurid reptile from the Early Cretaceous Birdrong sandstone of Western Australia. *Records W. Australian Museum*, **18**, 263-273.

Fraas, E., 1910. Plesiosaurier aus dem oberen Lias von Holzmaden. *Palaeontographica*, Stuttgart. **57**, 105-140

Hampe, O., 1992. Ein grossuchsiger Pliosauridae (Reptilia: Plesisosauria) aus dem Unterkreide (oberes Aptium) von Kolumbien. *Courier Forschungsinstitut Senckenberg*, **145**, 1-32

Halstead, L.B., 1989. Plesiosaur Locomotion. *Journal of the Geological Society*, London. **146**, 37-40.

Lingham-Soliar, T, 1992. The tylosaurine mosasaurs (Mosasauridae, Reptilia) from the Upper Cretaceous of Europe and Africa. *Bulletin de l'Institut Royal des Sciences Naturelles de Belgique* **62**, 171-194

Lingham-Soliar, T, 1995. Anatomy and functional morphology of the largest marine reptile known, Mosasaurus hoffmanni (Mosasauridae, Reptilia) from the Upper Cretaceous, Upper Maastrichian of the Netherlands. *Phil. Trans. R. Soc., London B*, **347**, 155-180.

Longman, H.A. , 1924. A new gigantic marine reptile from the Queensland Cretaceous. *Memoirs of the Queensland Museum*, Brisbane. **8**, 26-28.

McGowan, C., 1987. *The raptor and the lamb: predators and prey in the living world.* Henry Holt

McGowan, C. and Motani, R., 1999. A reinterpretation of the Upper Triassic ichthyosaur Shonisaurus. *Journ. Vertebrate Paleontology* **19**, 42-49

McHenry, C., Martill, D.M., Cruickshank, A.R.I. and Noè, L.F., 1996. Just when you thought it was safe to go back to the water - the biggest pliosaurs yet? *Palaeontological Association 40th Meeting, Birmingham 16-19 December 1996.* Abstracts, 22.

Martill, D.M., Taylor, M. A. and Duff, K.L. with contributions by Riding, J.B. and Brown, P.R., 1994. The trophic structure of the biota of the Peterborough Member, Oxford Clay Formation (Jurassic), UK. *Journal of the Geological Society*, **151**, 173-194.

Massare, J. A., 1988. Swimming capabilities of Mesozoic marine reptiles: implications for method of predation. *Paleobiology.* **14**, 187-205

Romer, A.S., 1959. A mounted skeleton of the giant plesiosaur Kronosaurus. *Brevoria*, 112, 1-15.

Tarlo, L.B., 1959. Stretosaurus gen. nov.: a giant pliosaur from the Kimmeridge Clay. *Palaeontology*, **2**, 39-55

Tarlo, L.B., 1960: A review of the Late Jurassic Pliosaurs. Bulletin of the British Museum (Natural History) *Geology*, **4**, 147-189.

Taylor, M.A., 1992. Functional anatomy of the head of the large aquatic predator Rhomaleosaurus zetlandicus (Plesiosauria, Reptilia) from the Toarcian (Lower Jurassic) of Yorkshire, England. *Phil. Trans. R. Soc. Lond. B* **335**, 247-280.

Taylor, M.A, and Cruickshank, A.R.I., 1989. The Barrow Kipper, 'Plesiosaurus' megacephalus (Plesiosauria, Reptilia) from the Lower Lias (Lower Jurassic) of Barrow-on-Soar, Leicestershire. Trans. *Leicester Literary and Philosophical Society*, **83**, 20-24

Thulborn,T. and Turner, S., 1993. An elasmosaur bitten by a pliosaur. *Modern Geology*, **18**, 489-501.

Williston, S.W., 1897. Range and distribution of the mosasaurs. *Kansas University Quarterly*, **6**, 177-189.

Ziegler, B., 1992. *Guide to the Löwentor Museum.* Stuttgarter Beiträge zur Naturkunde. 27 (E)

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Geomorphology of the Lincolnshire Wolds: an Excursion Guide

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Abstract: The chalk-capped Lincolnshire Wolds exhibit a range of geomorphological features created largely by river action, and a wealth of smaller features generated under glacial and periglacial conditions. An excursion from the southern sandstone country to the Humber shore visits escarpments, dry valleys, erosion surfaces and meltwater spillways.

The Pleistocene lasted some two million years, of which at least half was cold, with sub-Arctic to Arctic conditions in Lincolnshire. Due to uncertainties about correlation and nomenclature of events before the Devensian, and the central position of Lincolnshire in relation to the glaciations of eastern England, only the terms pre-Devensian and Devensian are used in this text. Pre-Devensian events include the deposition of chalky boulder clay, notably the Calcethorpe Till. Immediately before the Devensian, the warm interglacial (usually referred to as the Ipswichian) saw the main incision of the Wolds valleys under full forest cover, while its high sea level probably trimmed the marine cliff along the eastern edge of the Wolds. Most of the features described in this excursion evolved during the Devensian, which lasted for 90,000 years, with only about 20,000 years of actual glaciation, notably in the substage 25,000 to 15,000 years BP. The Devensian saw a series of glacial advances between short less cold interstadials; there were long periods of periglacial landscape evolution.

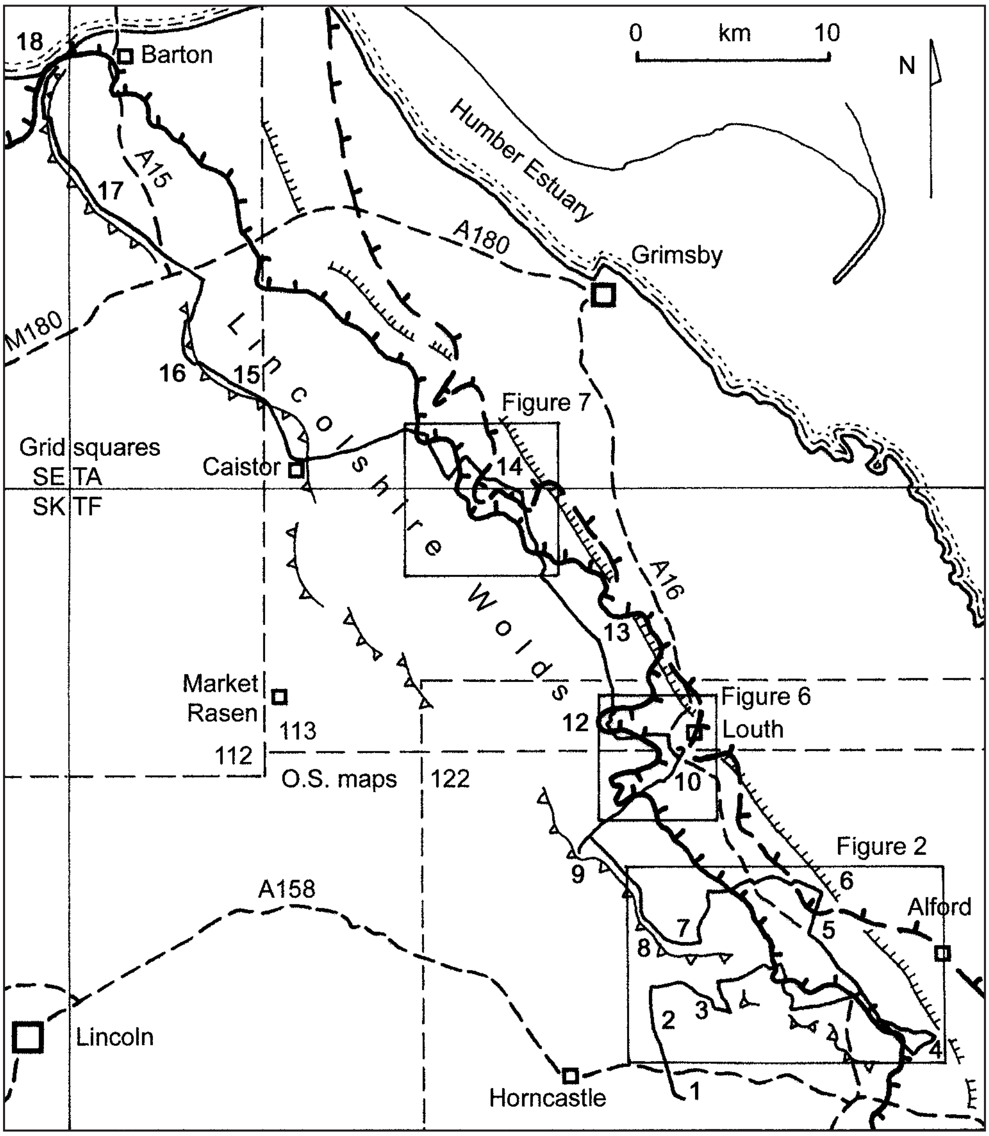


Figure 1. Major features of the Lincolnshire Wolds, and the excursion route. [Key as in Figure 7, except that roads are shown as single lines]

During the Devensian, eastern Lincolnshire was invaded from the northeast by ice that originated in Scotland, northern England and Scandinavia. Its maximum advance is marked by moraines at Stickney in the Fens and Horkstow in the Ancholme valley, and by the location of marginal meltwater spillways in the eastern Wolds. The ice over-rode the frozen chalk of an old marine cliff, and penetrated valleys that had been draining to the east, so that proglacial lakes were impounded by ice until they overflowed into alternative outlets. During the melt-back of the ice, there were periods of stillstand when blocks of dead ice were isolated, and a further series of spillways and associated outwash sands and gravels developed around these. Further melt-back away from the Wolds allowed a short period of fluvial erosion. This was followed by a final re-advance of ice and the cutting of yet more spillways, that remain the youngest and freshest in the landscape, before the final phased recession of ice from the Wolds area (Straw 1958, 1969)

This excursion extends to about 130 km by road across the southern and northern Lincolnshire Wolds. It could be covered in a single long day, as few locations require walking far from the car. Alternatively it can be broken to cover a weekend for those who wish to walk a bit further. The excursion demonstrates features associated with the glaciation, notably some of the seventy meltwater channels, two-thirds of them cut into the Chalk, together with the escarpments and erosion surfaces. All the features can be viewed from public roads or footpaths, so no permissions are required. It would be difficult to follow this excursion without good maps, and the text does not contain precise route details. The relevant OS 1:50,000 maps are sheets 112, 113 and 122. The 6-digit numbers in brackets after locations are the grid references, which are in squares TF (high northings), TA (low northings), SE (high eastings).

The following abbreviations are used throughout this paper:
LWTNR: Lincolnshire Wildlife Trust Nature Reserve;
RIGS: Regionally Important Geological/Geomorphological Site;
SSSI: Site of Special Scientific Interest.

Upper Cretaceous	Upper Chalk	Northern Wolds
	Middle Chalk	Central and Southeast Wolds
	Lower Chalk	
	Red Chalk	Southwest Wolds and scarp faces
Lower Crataceous	Carstone	
	Roch Formation	
	Tealby Formation Tealby limestone	
	Spilsby Sandstone	
Juarassic	Kimmeridge Clay	Vales to west

Table 1. The sequence of beds seen during the Wolds excursion, and geomorphological features on them.

The southeastern Wolds

Start east of Horncastle (Fig. 1) at the Snipe Dales Nature Reserve (LWTNR), where there is a car park at Winceby (320682). This is sandstone country lying below the chalk-capped Wolds to the north. Walk a short distance into the reserve to a viewpoint (**Locality 1**, 322684) over the valley, where there is an interpretation board. Since its deposition in an earlier pre-Devensian glaciation, much of the covering of chalky boulder clay (Calcethorpe Till) has been removed. Valleys have been eroded through the Spilsby Sandstone into Kimmeridge Clay, and spring sapping has cut recesses back into the sandstone. On the south side a tougher band of sandstone forms a small bluff by the viewpoint, but on the warmer, south-facing, north side the slope is gentler, and the bluff is masked by solifluction deposits most probably formed during periglacial conditions of the Devensian stage.

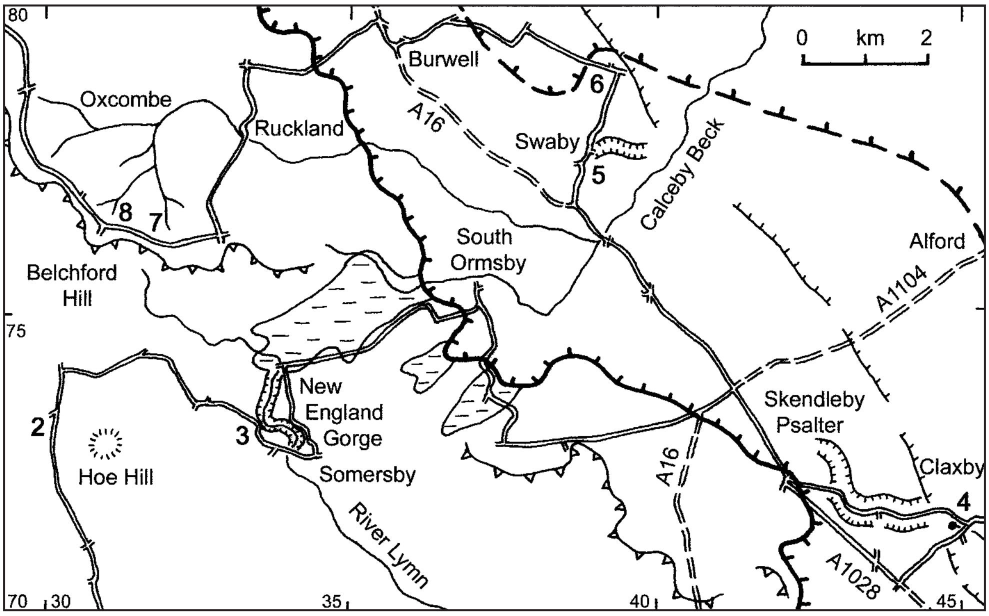
Head north through Greetham, and follow the ridge of Lower Cretaceous Tealby Formation capped by Calcethorpe Till, north to **Locality 2**, at 302733. A view east is of the steep-sided Hoe Hill outlier (RIGS). The flat top marks the outcrop of the Roach Formation (Roachstone), a hard calcareous sandstone; this has been separated by the headward extension of tributaries of the River Lymn, through a combination of fluvial and mass movement processes largely under a cold periglacial climate.

Continue north, and then turn east to descend the slope of the Lower Cretaceous ridge at Nab Hill, onto the wide bench of Spilsby Sandstone, and continue through Salmonby, onto a narrow road towards Somersby. At a sharp right bend (335732), the deep, steep-sided New England Gorge (SSSI) lies below to the left, but vegetation usually prevents a clear view.

The impressive New England Gorge (**Locality 3**) is a glacial spillway, or overflow channel (Straw, 1957). During the Devensian glaciation the eastward-flowing course of the Tetford-Calceby Beck was blocked by advancing ice and a pro-glacial lake formed in the broad depression east of Tetford. The water escaped over a low watershed into the River Lymn system, and cut the gorge down through the Spilsby Sandstone into the Kimmeridge Clay, effecting a permanent diversion of the Tetford Beck (Fig. 2). A short distance further on the road crosses the mis-fit stream as it leaves the gorge.

Turn left in Somersby, and pass the heads of two spring-sapped subsequent tributary valleys of the gorge, before gaining a view of the head of the gorge back to the left at the T-junction. Head east towards South Ormsby, passing between the broad floor of the Tetford pro-glacial lake to the north and hills capped by small outliers of chalk to the south. Turn south through Brinkhill, and rise onto a broad ridge capped by Red and Lower Chalk, that extends to Ulceby.

Figure 2. Some morphological features of the southeastern Wolds (after Straw, 1957). [Key as in Figure 7]



Continue southeast on the A1028 along the ridge, and from the crossroads at 439706, descend towards Claxby. At the foot of the hill, Claxby Spring (**Locality 4**, 450714, RIGS) is the source of Burlands Beck. It has a headwall of chalk, cut back into the general slope that marks the eastern boundary of the Wolds, and is probably a degraded marine cliff that pre-dates the Devensian glaciation. Turn west up the Skendleby Psalter valley, which is dry and drift-free. Strongly fault-guided, this has been fluvially deepened after recession of the Devensian ice from the Wolds, so that the Carstone is now exposed along the valley floor below the chalk (Straw, 1958).

Head north on the A16 across the 100 m plateau on chalk, and descend to cross the outwash gravel terraces of the Calceby Beck valley. Leave the main road to go into Swaby village. Turn right into Pado Lane, and the walk right along Valley Lane and the footpath beyond into Swaby Valley (**Locality 5**, 391776, LWTNR, SSSI). This is a fine example of a meltwater channel (Fig. 3) that was associated with a decaying block of ice to the south, in the valley between Swaby and Calceby. A sinuous steep-sided feature was cut into the Chalk, and is unusual because gravel terraces survive within it. Swaby Beck is permanently diverted through the gorge; its old valley southwards from Swaby is now partly blocked by glacial drift (Straw, 1961a).

Continue north to Meagram Top (**Locality 6**, 392789), near the eastern edge of the Wolds, where there is a good view across the old cliff line to the Middle Marsh - an undulating and locally hummocky area of Devensian till on a wave-cut platform of chalk. Continue west towards Burwell, and follow the upper course of Swaby Beck. Just east

Figure 3. The open entrance to the Swaby Valley spillway. [Photos by author]

Figure 4. The scarp face of the chalk northwest from Belchford Hill.

of Burwell, the road passes through a small meltwater channel that is still occupied by a stream; the old valley (360792) curves round the south side of a small chalk knoll. At Burwell turn right onto the A16 and in a few hundred metres just through the village turn left towards Maidenwell.

From the A16 at Burwell, a minor road rises westwards through a good example of a dry valley system in chalk; its valley sides are marked by darker streaks in the soil or as crop marks that lie over shallow, filled, linear gullies. Turn south through Ruckland where a major tributary of the Calceby Beck has cut down into the Tealby Formation. Climb up onto the crest of the Wolds, and turn right along the ancient trackway of the Bluestone Heath Road. **Locality** 7 is a layby viewpoint with interpretive board at 317762. To the southeast, the scarp of the Chalk caps the eastern part of the southern Wolds, and a tiny outlier of Carstone caps the knoll at Glebe Farm in the foreground. Southward the country is based by the Tealby Formation and Spilsby Sandstone. To the southwest and west, the ridge of Lower Cretaceous rocks, partly capped by Calcethorpe Till, extends through Fulletby to Greetham; it overlooks to the west the valley of the River Waring which crosses through the ridge at Belchford.

Stop at the top of Belchford Hill (**Locality 8**, 309763) for a good view northwest of the scalloped face of the chalk escarpment (Fig. 4). This is formed by Lower Chalk, whose outcrop is reduced to a ridge less than 200 m wide where a dendritic system of deep valleys is cut into the dip slope. The rounded amphitheatres at these valley heads (well seen here to the north at Oxcombe), and the thick deposits of chalk gravel on the valley floors, indicate that final stage of erosion took place under Devensian periglacial conditions.

Continue north, past two more steep valley heads to the east, and cross the A153 onto the summit plateau of the Wolds, the High Street Bluestone Surface. At 150 m, this is the highest and oldest of the erosion surfaces of the Wolds, dating from the end of the Tertiary (Straw, 1961b).

Turn left at 272818 to go over the crest of the Wolds escarpment, and down to Red Hill (LWTNR; SSSI) where there are two small roadside parking areas (**Locality 9**, 265806). Below the disused chalk quarry there is a fine exposure of Red Chalk and Carstone. The lower part (which is becoming increasingly masked by weathering and scree accumulation) shows the beds curving downslope as they pass into a capping of angular rubble; this is a fine example of a gelifluction deposit (the material generally known as head) that has been produced by frost shattering, solifluction and mass movement (Robinson, 1971).

From the top of the quarry there are good views of the Spilsby Sandstone bench at the foot of the hill which is notched by a small stream flowing against the dip of the rock. This joins the Scamblesby Beck which has cut down to the Kimmeridge Clay, producing strong bluffs of sandstone through Goulceby village. The gap between the two exposures of Red Chalk was created as a wash-out during the torrential rain on 29 May 1920 that caused the destructive flooding in both Horncastle and Louth (see below). In the field immediately south across the road from the gap in the quarry rim, the run-off water of this one storm cut a gully and deposited a debris fan towards Goulceby. Despite ploughing, it can still be identified by its soil colouration or crop marking. To the southwest Imber Hill is capped by Tealby Limestone, and on a clear day it is possible to see beyond to Lincoln Cathedral on its ridge.

The Wolds above Louth

Approaching Louth on the A153 from the south, the brow of Stanmore Hill (**Locality 10**, 315854) offers a fine view north to the tree-lined gorge of Hubbard's Hills, with the bypass curving round it (Fig. 5) and a shallow nick across the spur to the northwest (just off the photograph). In the Devensian glaciation a lobe of ice penetrated the Hallington valley, initially to just beyond Hallington village (Fig. 6). During its melt-back, the ice impeded the flow of spring meltwaters down the Hallington and Tathwell valleys, ponding them back into a deep lake. The first escape route north for the water was probably the shallow nick across the spur. Subsequently the water escaped over the spur a little further east, into the Welton valley, and a waterfall cut back rapidly into the chalk to create a gorge whose sides were then trimmed by frost action. It is likely that the gorge was created rapidly by powerful meltwater flows early in each summer; it may have been formed entirely within just 200-300 years.

Across the A16 bypass, turn left at the tollhouse along Halfpenny Lane into the Hallington valley. The lane cuts through the thick moraine that was deposited at the ice margin and ensured the permanent diversion of the Hallington Beck through its new gorge. There is a parking area at 315860, where a footpath leads through the classic open-ended gorge of Hubbard's Hills (**Locality 11**, RIGS). From the top of the steps from the car park, the broad pre-Devensian valley of Hallington Beck can be seen heading east past the tollhouse towards the Marsh.

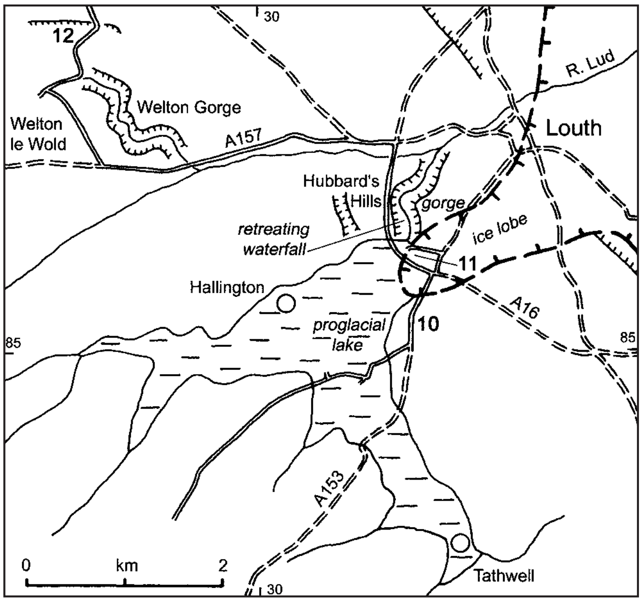


Figure 6. The ice-dammed lake in the Hallington valley; features labelled in italics were active in Devensian times. The main gorge, east of the A16, was cut by waterfall retreat; west of the A16, a higher, older overflow channel had been cut when the ice dam reached further up the valley. [Key as in Figure 7]

The last time the stream, which becomes the River Lud, was a raging torrent was on 29 May 1920, the occasion of the tragic Louth flash flood. On that Saturday, 114 mm of rain fell in less than three hours on the headwaters of the River Lud catchment. Gullies up to two metres deep were carved into fields, trees uprooted and bridges swept away. Rain began around 2pm, and around 5pm a debris dam which had built up at Little Welton gave way, so that a wall of water over four metres high swept towards Louth and its unsuspecting residents (after joining the already swollen Hallington Beck).

The narrow winding course of the Lud through Louth was constricted by terraced houses and industrial buildings. In 20 minutes the debris-laden flood waters cut through the town, destroyed over 50 houses, left another 250 in need of rebuilding, and claimed 23 lives. Brown and yellow mud from the chalk catchment left a clear floodmark on surviving buildings (Robinson, 2000).

Figure 5. The overflow channel at Hubbard's Hills.

Head west away from Louth on the A157 towards Lincoln. At 293869, a straight section of road dips across the south end of the Welton gorge. Further west, turn right through Welton le Wold to **Locality 12**, the disused gravel quarry (282882, SSSI). To the north, an exposure of whitish Calcethorpe Till survives, but the dark brown Welton Till and the flinty gravels and sands beneath it are now hidden by backfill. Derived Hoxnian tusks and teeth of elephant were recovered from the gravels in 1974, along with some Acheulian flint handaxes (Alabaster & Straw, 1976). East of the road there is an exposure of brown Devensian till; this was deposited on top of the eroded and much older gravels and tills at the limit of the Devensian ice penetration of the valley. Meltwaters escaped southeast from this whole area to cut the sinuous Welton gorge. The Welton deposits are evidence of the re-advance of ice from the east over the flinty gravel, and the periglacial emplacement of some of the material known as Calcethorpe Till (Straw, 1969).

The northern Wolds

Head north across the A131, over a broad plateau to **Locality 13**, a road junction above North Ormsby (270925) that offers the best views. This lies on the remarkably flat Kelstern Surface, which, at a level of 115-130 m, is probably a marine planation of early Pleistocene date (Straw, 1961b). It is largely veneered by less than 5 m of Calcethorpe Till, but both the rock platform and the till have been eroded at the margins by headward incision of valleys that drain both east and west. The steep eastern slope of the Wolds is a continuation of the degraded cliff seen at Locality 4. The valleys to the east are floored by Devensian till that forms the hummocky Middle Marsh beyond and underlies the marine silts towards the coast.

Continue north across the Kelstern Surface and descend into Wold Newton by the large dry valley that is so typical of the upland chalk fluviokarst. At South Farm (245961), a prominent tree-lined meltwater channel called The Valley enters from the east. Beyond Wold Newton, a short-lived nineteenth-century brickworks exploited localised lacustrine deposits at Petterhills (238983). At East Ravendale, turn west along another meltwater channel that continues past West Ravendale (Fig. 7), where the face of a disused quarry on the right (225000, RIGS) exposes faulted Upper Chalk with tabular flints.

An old drift-blocked valley lies north from West Ravendale, but the road curves west through the deep dry Round Hill valley (**Locality 14**, 220003, RIGS). This is a fine example of a meltwater channel, with steep flanks, that are steepest on the outer sides of bends, a flattish floor and a constant gradient westward. Several channels in the West Ravendale and Hatcliffe area originated as marginal drainage features around wasting masses of ice (Fig. 7). The ice decay left low mounds of boulder clay and gravel, for example to the west of the exit from the Round Hill valley (213003).

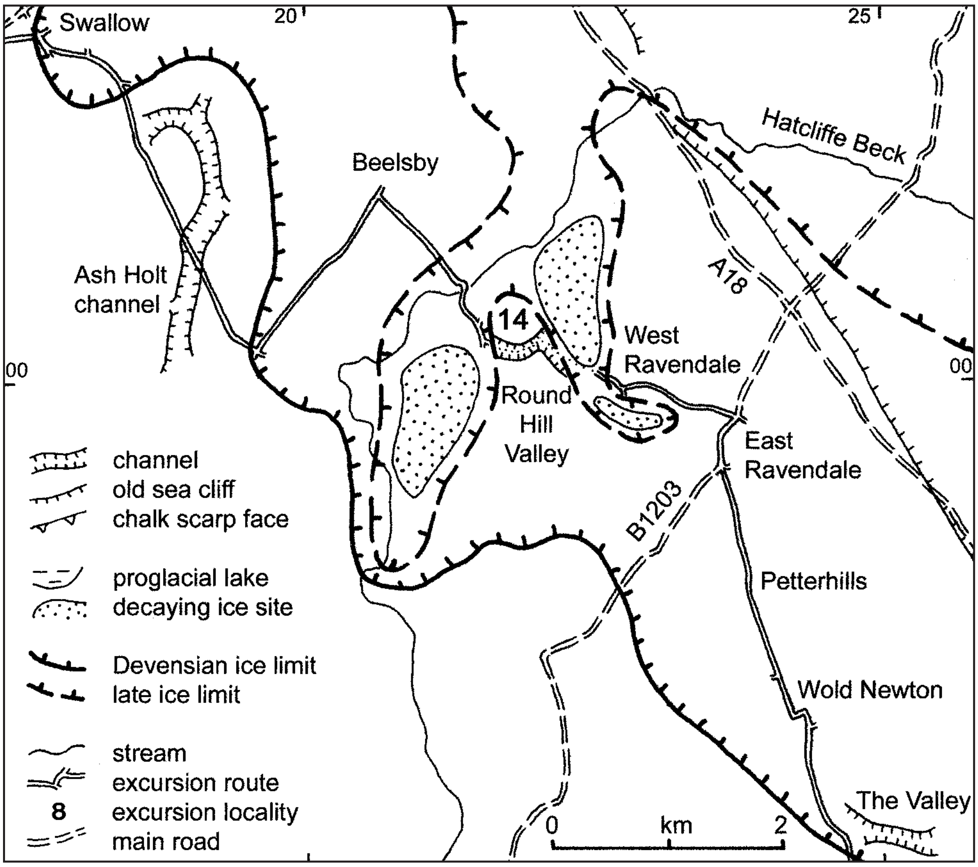


Figure 7. Ice margin features around West Ravendale, showing the sites of three masses of decaying ice left by the late Devensian melt-back of the main ice sheet that had moved in from the east (after Straw, 1961a). [Key applies also to Figures 2 and 6]

Continue north to Beelsby and south towards Croxby, but then turn north towards Swallow, to cross the Ash Holt channel at 191010. This has gently graded sides that are furrowed by shallow gullies, and contains a considerable deposit of blown sand, both indicating that it is somewhat degraded and older than the Round Hill channel (Straw, 1961a).

From Swallow join the A46 to ascend the chalk dip slope that is incised by dendritic dry valleys; at Caistor Top, regain the High Street Bluestone Surface at 150-170 m. Fork right onto the A1084 and descend the scarp through Caistor, thence across cover sands that are partly wind-blown; these are banked against the scarp face, which is fretted with steep dry valleys (Straw, 1963). At Clixby the road climbs the scarp again, where its alignment swings to northwest under the influence of a monocline in the underlying rocks. At Caistor, and further south, the profile of the Wolds scarp face is complicated by benches and knolls controlled by variations in erosional resistance of the Lower Cretaceous sequence of Carstone, Tealby Formation and Spilsby Sandstone. Around Clixby, these Lower Cretaceous rocks are pinched out between the Upper Cretaceous Chalk and the Jurassic Kimmeridge Clay. Consequently, northwards from Clixby, all the way to the Humber, the scarp has a lower and relatively simple form.

At the highest part of the road, above Owmby, **Locality 15** (078057) offers good views west across the Ancholme valley, where low mounds of Kimmeridge Clay are capped by pre-Devensian chalky boulder clay, and east down the dip-slope to the industrial sites of the Humber Bank. The narrow road down to Somerby meets the foot of the slope at **Locality 16** (065065) where there is a fine view southeast of the chalk scarp face.

Continue north through Bigby, over a shoulder of the chalk escarpment, and down to Melton Ross. This lies in the Barnetby Gap, which was exploited by meltwaters flowing west from a Devensian ice front that stood at Kirmington, about 4 km east of the road junction (Twidale, 1956). Head northwest on the minor road that passes under the two motorways and between two disused chalk quarries above Elsham. Keep to the scarp crest to Worlaby Top (**Locality 17**, 020145). This spot offers fine views southeast of the Wold escarpment, west across the Ancholme valley and the Jurassic limestone escarpment to the Scunthorpe steelworks, and east down the chalk dip slope towards the Humber Bank. From the high point on Saxby Wolds (around 000165) there are good views of the River Humber and the Yorkshire Wolds.

Continue on the ridge top road to the T-junction at Horkstow Wolds, then descend the scarp and continue north to South Ferriby. Cross the A1077 and park on a track at 989213. Walk along the unmetalled track and follow the footpath down to the Humber shoreline (SSSI).

The Humber Gap is a very old feature that probably originated millions of years ago in concert with other east-flowing rivers of eastern England. The river would have initially flowed at a level well above the present-day crest of the chalk escarpment, and its course may have been influenced by east-west faults that are known to exist under and near the Gap. Prior to the Devensian glaciation, the River Humber flowed due east to reach the North Sea near Withernsea through a valley that is now buried by Devensian deposits (but is known from borehole records). Devensian ice passed westward through the Humber Gap, ponding water in the Ancholme, Trent and Ouse valleys. At a later stage, after the ice had melted from within the Humber Gap, an ice

Figure 8. Dark silts and glacial till overlie frost shattered chalk at the South Ferriby cliff; the white material above the till is chalk waste from a quarry.

front lay east of Hull; this deflected the re-established Humber towards the southeast, into the course that it has since retained.

Where the footpath descends to the shore, **Locality 18** (993218) there is the unusual sight of raised saltmarsh on a beach of discoidal pebbles of chalk. To the northeast, a low cliff exposes till overlain by a terrace deposit of unstratified sandy chalk gravel that was probably a solifluction sheet of frost-shattered chalk from a dry valley to the southeast. The gravels exhibit good frost wedge structures and soil-filled pipe features. Further northeast, the Devensian till is exposed resting on a planed surface of disturbed and cryoturbated chalk (Fig. 8). Lenses of laminated sandy silt and pebbles between the chalk and the till indicate the margin of an ice-dammed lake that probably existed as ice was melting away in the Humber Gap. The purplish-brown till is up to 8 m thick, and local oxidation and decalcification, from Flandrian weathering, has given the top 2-3 m a reddish-brown colouration (Catt, 1977; Robinson, 1988).

Acknowledgements

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References

Alabaster, C. & Straw, A., 1976. The Pleistocene context of faunal remains discovered at Welton le Wold, Lincolnshire. *Proceedings Yorkshire Geological Society*, **41**, 75-94.

Catt, J. A., 1977. *Guidebook for Excursion C7*: Yorkshire and Lincolnshire. International Union for Quarternary Research.

Robinson, D. N., 1971. Geology and scenery of the Lincolnshire Wolds: excursion report. *Mercian Geologist*, **4(1)**, 63-68.

Robinson, D. N., 1988. Geology and scenery traverse of north Lincolnshire: excursion. *Mercian Geologist*, **11(3)**, 195-200.

Robinson, D. N., 2000. *The Louth Flood 29th May 1920*. Louth Naturalists' Antiquarian & Literary Society, 2nd edition, 40pp.

Straw, A., 1957. Some glacial features of east Lincolnshire. *East Midland Geographer*, **7**, 41-48.

Straw, A., 1958. The glacial sequence in Lincolnshire. *East Midland Geographer*, **9**, 29-40.

Straw, A., 1961a. Drifts, meltwater channels and ice-margins in the Lincolnshire Wolds. *Transactions of the Institute of British Geographers*, **29**, 115-128.

Straw, A., 1961b. The erosion surfaces of east Lincolnshire. *Proceedings Yorkshire Geological Society*, **33(2)**, 149-172.

Straw, A., 1963. Some observations on the "Cover Sands" of North Lincolnshire. *Transactions of the Lincolnshire Naturalists' Union*, **XV(4)**, 260-269.

Straw, A., 1969. Pleistocene events in Lincolnshire: a survey and revised nomenclature. *Transactions of the Lincolnshire Naturalists' Union*, **XVII(2)**, 85-98.

Twidale, C. R., 1956. Glacial overflow channels in north Lincolnshire. *Transactions of the Institute of British Geographers*, **22**, 47-54.

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LANDMARK OF GEOLOGY IN THE EAST MIDLANDS

Peat subsidence at the Holme Post

The fenlands along the eastern borders of the East Midlands are Britain's largest area of peat soils. Prized by the farmer as a rich organic soil, peat is dreaded by the engineer because it is weak and compressible and is highly shrinkable when it is drained. When the natural marshes of peat lands are drained to make them useable and inhabitable, the ground surface subsides. It's a phenomenon known worldwide, and the world's finest record of land subsidence on peat is provided by the Holme Post, just 9 km due south of Peterborough cathedral.

The fens occupy a large swathe of lowland that broadly follows the outcrop of the Jurassic Oxford Clay. South and inland from the zone of estuarine sedimentation adjacent to the Wash, peat growth has dominated surface processes throughout post-glacial times. The black fens originated as a sea of waterlogged vegetable matter, but only really earned their name when they were drained to expose the black peat soils that could be farmed.

Drainage of the fens

Some small areas of the fens were drained by the Romans, but the main engineering works that drained huge areas date largely from the 1600s. Cornelius Vermuyden brought his experience from Holland to control the River Ouse and drain the Bedford Levels in 1630 and 1650. Control of the River Nene was ahead of its time. The river's original course took a great loop southwards from Peterborough, until the Bishop of Ely, John Moreton, had the channel cut straight through to Wisbech before 1600.

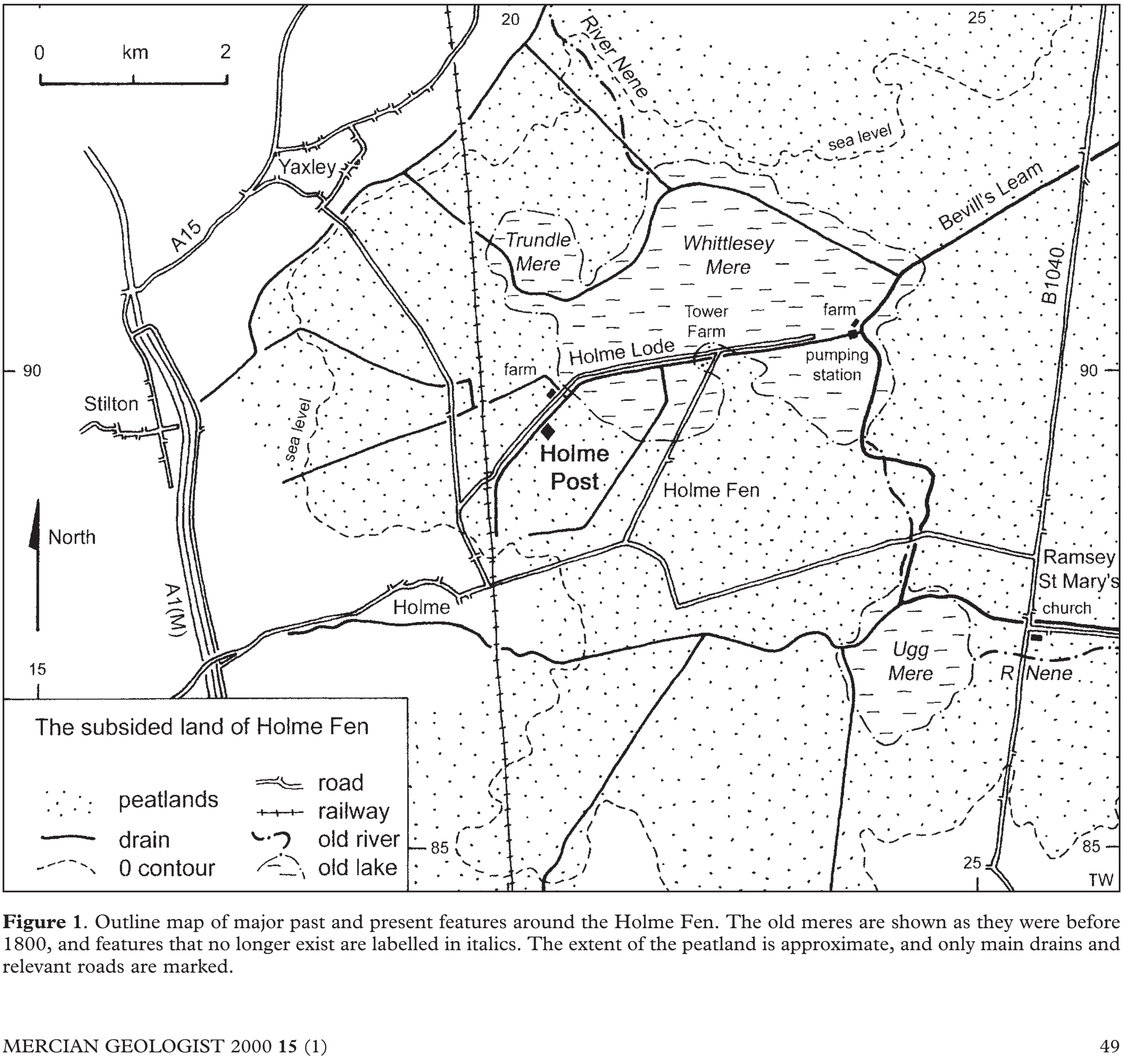

Figure 1. Outline map of major past and present features around the Holme Fen. The old meres are shown as they were before 1800, and features that no longer exist are labelled in italics. The extent of the peatland is approximate, and only main drains and relevant roads are marked.

Bevill's Leam and the Twentyfoot River were cut in later years to drain a swathe of new farmland south of the Nene (that was already in Moreton's channel). Ground subsidence, that followed the fen drainage, was soon recognised as inevitable and relentless. Pumping stations were built to raise water into the rivers from the new drains on the subsiding peat, and the rivers had their levels maintained between new embankments in order to ensure their gradients to the coast.

Holme Fen lies just east of the villages of Holme, Stilton and Yaxley, that all lie on clay “upland” only slightly higher than the drained fen. The sea-level contour almost follows the western margin of the peat fens (Fig. 1). Before drainage, the fens contained many shallow lakes, of which Whittlesey Mere was one of the largest. The River Nene originally flowed through this mere, then south to Ugg Mere, before turning east towards the Ouse. By 1851, silting and peat expansion had reduced Whittlesey Mere to about 400 ha and only a metre deep. In that year the mere disappeared, when new drains carried waters to a pumping station and up into Bevill's Leam. The drainage turned both the mere and the Holme Fen into useable farmland, but subsidence followed.

The Holme Post

In anticipation of the ground subsidence, the landowner had an oak pile driven through the peat and firmly embedded in the underlying clay; he then cut the top level with the ground in 1851 and used it to monitor the peat subsidence. A few years later, the oak post was replaced by a cast iron column, that was similarly founded on timber piles driven into the stable clay, with its top at the same level as the original post. This is the Holme Post that survives today (at NGR TL203895). As it was progressively exposed it became unstable, and steel guys were added in 1957, when a second iron post was also installed 6 m to the northeast. Both posts are standing today.

The post now rises 4 m above the ground, and provides an impressive record of the ground subsidence (Fig. 2). Sea level is close to the collar that links the steel guys, and this is now the lowest land in Britain. It is readily accessible, beside the one road that loops across Holme Fen east of the railway (Fig. 1). Though the subsidence has now slowed to a rate that is only recognisable over a decade or more, a series of isolated observations clearly records the ground movement since the peat was drained (Fig. 2).

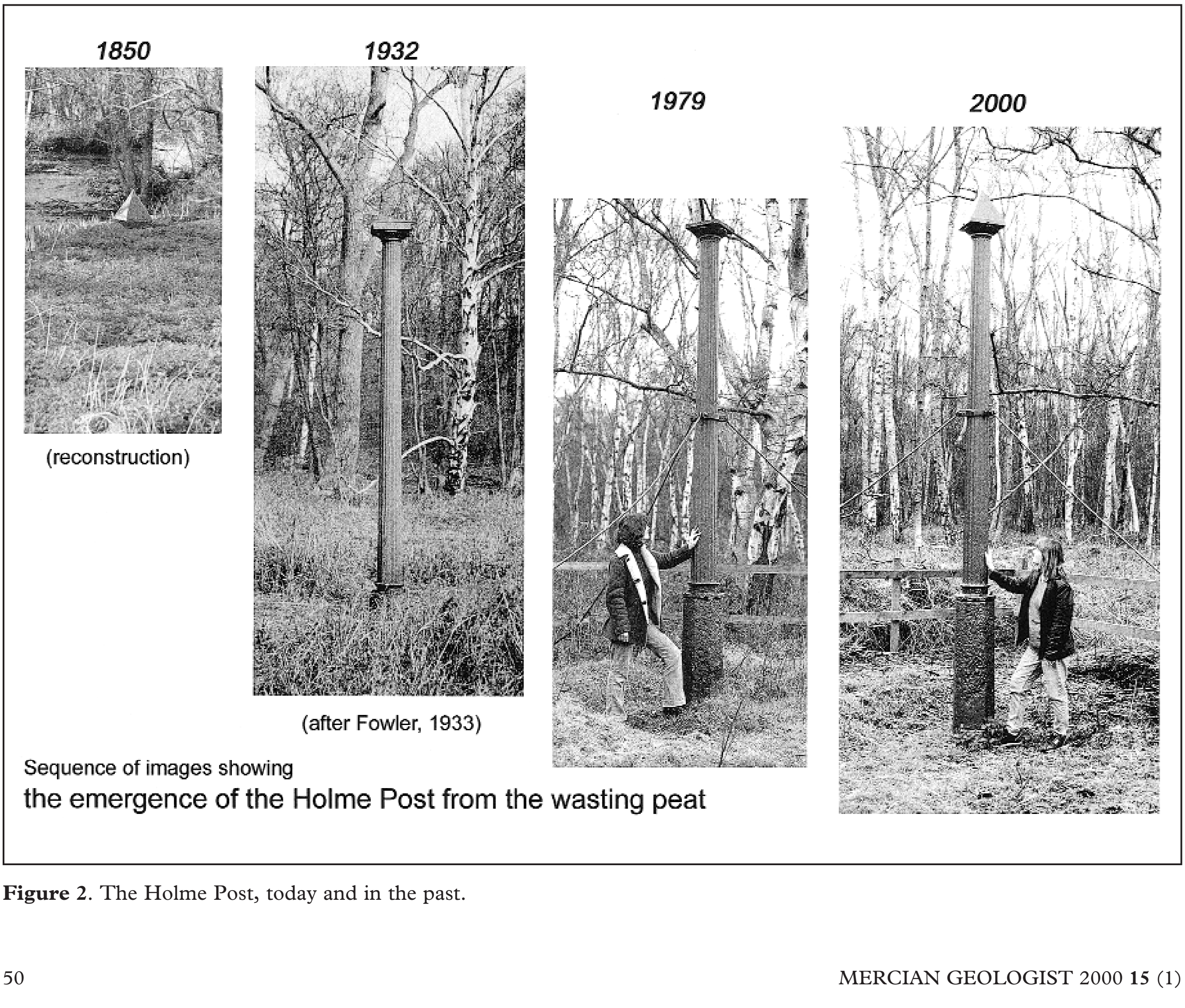

Figure 2. The Holme Post, today and in the past.

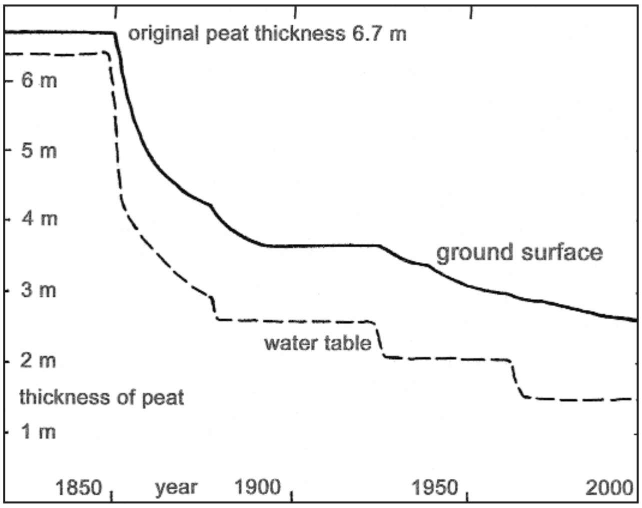

Figure 3. The record of ground subsidence on the peat over 150 years at the Holme Post, correlated with water table levels that declined in response to the successive stages of pumped drainage.

There is a clear correlation between the ground subsidence and the land drainage. The ground in Holme Fen subsided by nearly 2 m in the first decade after its initial drainage, and thereafter subsided at a declining rate. In the period 1890-1925, there was no measurable subsidence while birch woods progressively replaced the arable farmland. Since then renewed pumping has lowered the water table and induced further slow subsidence. This appears to continue today, but is on a smaller scale than the annual ground level fluctuations of about 50 mm (as the land absorbs and loses water).

Peat subsidence

Ground subsidence on peat (without any loading compression due to buildings) is due to a combination of consolidation and wastage. Consolidation causes the rapid initial movement; the loss of water pressure allows the extremely porous peat to collapse and restructure, thereby increasing its density but greatly reducing its volume. The peat of Holme Fen subsided by 1.8 m when the water table first declined by 2.8 m. This subsidence, that was 65% of the water table decline, is typical of initial subsidence rates recorded worldwide; the ratio fell to 30% after subsequent phases of renewed drainage of the partly consolidated peat.

Wastage is a subsidence process that is unique to peat soils. Drained peat simply oxidises into various gases and therefore disappears, in a perfectly natural process of biodegradation. Saturated peat is stable because oxygen cannot reach it. But sadly, as soon as unusable wetland is drained to create farmland, it immediately starts to disappear by wastage. This causes surface lowering of about 10 mm/year at Holme Fen, but greater wastage rates occur where the water table is deeper (exposing more dry peat) and in warmer climates (where oxidation is more rapid). In drained land, wastage continues until all the peat is gone. Peat is a wasting asset – it can be drained and farmed only at the cost of its inevitable destruction. The area of peatlands in the Fens is less than half of what it was 400 years ago, but fortunately the exposed underlying clay can support productive agriculture.

Peat creates unusual problems for engineered structures due to its subsidence and also its negligible strength when saturated. Older farmhouses in Holme Fen stand on timber piles that are founded in the underlying clay. Piled buildings remain stable while the ground subsides around them; because of this, Ramsey St Mary's has one of the many fenland churches now entered up a flight of steps. Also on piles, both Tower Farm and the farmhouse beside Holme Lode (Fig. 1) post-date the fen's initial drainage and rapid subsidence, so they stand only a little above the surrounding ground. The Whittlesey Mere pumping station (rebuilt in 1961) and the farm beside it are both stable on the silty sediments along an old channel of the Nene at the edge of the mere. Drained peat does have a low bearing capacity, and many later buildings are founded on rafts that impose minimal loading on the peat.

Roads across the peat were traditionally built on banks of faggots, peat and bundles of brushwood, so that they literally floated on the mire. The East Coast railway crosses the western edge of Holme Fen. It was built, just before the fen was drained, on a low embankment of faggots and peat sods; this was constructed slowly while it settled into the mire, squeezing and densifying the peat without rupturing it, until it could bear the load of the ballast and the trains. A hundred years later the track was still subsiding by 10-20 mm/year, but it now appears to rest on a buried mass of fill that reaches to the clay, having squeezed the peat out to the sides. At the level crossing on the approach to the Holme Post, the track is in excellent condition, though now well above fen level; and amplified vibrations from a passing train are a reminder of how unstable the peat is on either side of the line.

Literature

Fowler, G.., 1933. Shrinkage of the peat-covered fenlands. *Geographical Journal*, **81**, 149-150

Hutchinson, J.N., 1980. The record of peat wastage in the East Anglian fenlands at Holme Post, 1848-1978AD. *Journal of Ecology*, **68**, 229-249.

Waltham, A.C., 1989. *Ground subsidence*. Blackie, 202pp.

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REPORT

Morley Quarry, Charnwood Forest

Precambrian and Triassic rocks are on view at Morley Quarry [SK 4765 1785] at the northern extremity of Charnwood Forest. The site is easily reached on foot from the Cricket Club car park along Morley Lane (Fig. 1), south of the A512 at Shepshed. The quarry represents a sizeable former working for building stone, and it constitutes a site that is both attractive and educational. In 1994, Charnwood Borough Council declared it a Local Nature Reserve and it has since been upgraded to a RIGS. Extensive remedial work has been carried out on the quarry faces, but although the rocks can be viewed in complete safety from the central part of the quarry, it is still advisable to wear a hard hat when examining them close up. The geological scene is set by colourful explanatory notice boards placed at intervals around the quarry. Further information about the site is provided in a leaflet that can be obtained from Charnwood Wildlife, Southfields Road, Loughborough LE11 2TN.

Precambrian rocks

The quarry exposes magnificent sections in late Precambrian rocks of the Ives Head Formation. This unit forms part of the Blackbrook Group, and its strata are of particular interest in being among the oldest outcropping representatives of the Charnian Supergroup. The eastern quarry face shows about 40 m of massive to thinly bedded lithologies variably composed of mudstones, siltstones and sandstones (Fig. 2). Although these beds are of obvious sedimentary aspect, thin sections show that they consist mainly of volcanic particles, some of which are of pyroclastic derivation; they are therefore described as *volcaniclastic*. Notable in the lower part of this succession are graded sandstone beds up to several metres thick. The basal parts of these sandstones are completely unbedded and very coarse-grained, with sporadic, pebble-sized clasts that include laminated volcaniclastic siltstone. Thin sections show that the coarse sand-size grains are mainly composed of euhedral or fragmented crystals of plagioclase and quartz, together with lithic grains of vesicular-textured dacite and tuff, the latter commonly preserving the outlines of volcanic glass shards. There is an upward transition into medium-grained sandstone, with diffuse parallel stratification, then to a thinly bedded top of parallel layers of volcaniclastic mudstone and siltstone.

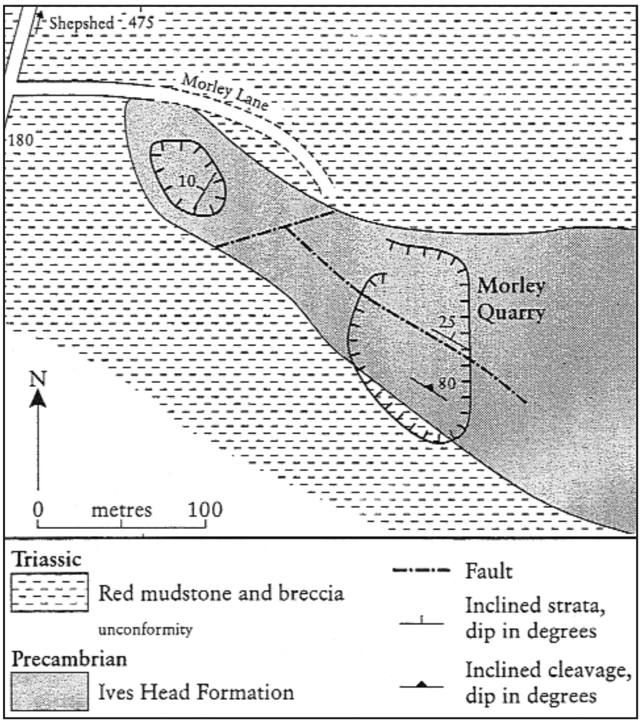

Figure 1. Geological sketch map of Morley Quarry.

These thick graded beds are interpreted as the deposits of turbidity currents, in which sand- to gravel-size grains were suspended by turbulence within plumes of sediment. This material flowed down the slopes of the active Charnian volcanic arc and accumulated in the surrounding seas (Moseley and Ford, 1989). Turbidites can be triggered by earthquakes, which commonly destabilise layers of unconsolidated sediments previously deposited along the basin margin, but they may also represent the distal, subaqueous continuations of pyroclastic flows erupted directly from volcanoes. There is little evidence to show the true origins of the Morley Quarry examples, however, since all of the textures and fabrics seen here are the result of depositional processes. Thus the structureless, coarse-grained facies, at the base of each graded sandstone bed, corresponds to a suspension-sedimentation stage of deposition, when grains were deposited directly from the suspended load of the turbidite without forming bedding structures. The incoming of finer-grained and better-stratified facies progressively higher up the bed, within the residual part of the turbidite flow, reflects more extensive sedimentary reworking. These upper beds represent the traction-sedimentation stage, when grains were accumulated from the bed-load of the turbidite (Lowe, 1982).

An added dimension to this site is provided by the findings of research drilling carried out in the quarry by the BGS as part of an investigation into the geothermal potential of Britain. The borehole section (Pharaoh and Evans, 1987), encountered a further 541 m (apparent thickness) of strata belonging to the Ives Head Formation and then entered a sequence consisting mainly of massive, grey, feldsparphyric dacite, interpreted as lava flows. This lower unit extends between 541 m and the base of the borehole at 835.5 m, and has been named the Morley Lane Volcanic Formation (Carney, 1994); it is not exposed in Charnwood.

The northeasterly Charnian dip, seen at the quarry, was imposed during the regional folding event that formed the main Charnian anticline. A

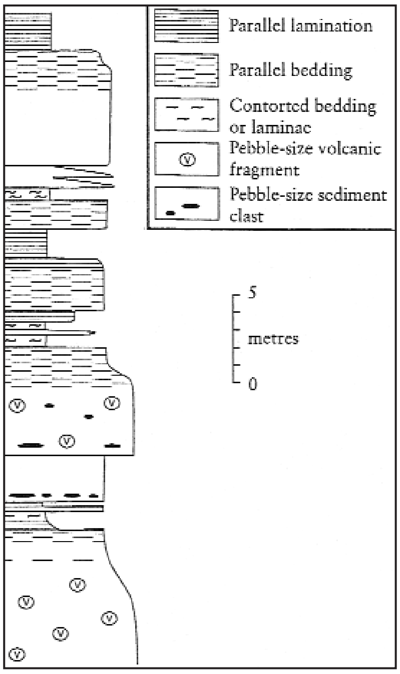

Figure 2. Lithological log of a measured section along the eastern face of Morley Quarry.

Figure 3. The upper southern face at Morley Quarry, showing the sharp unconformity between massive Precambrian rocks and poorly bedded Triassic breccia. The paler blocky deposit at the very top is the head.

highly penetrative cleavage fabric is visible as a faint foliation trending westnorthwest. The minerals defining these cleavage planes were crystallised at upper greenschist metamorphic grade, at the time of the folding, and radiometric determinations soon to be published will show that this deformation was not Precambrian, but was part of the Acadian (late Silurian to early Devonian) orogenic event. On the western quarry face, the cleavage, accentuated by weathering, shows broad crenulation and folding both within and adjacent to a westnorthwest fault (Fig. 1). This is clear evidence for a second, brittle (i.e. non-penetrative) phase of deformation; it possibly followed closely from the imposition of the cleavage, but could also be much younger, perhaps representing structures formed during Variscan (end-Carboniferous) earth movements.

Younger rocks and drift

Details of the early Triassic unconformity are magnificently displayed along the southern quarry face (Fig. 3). The Charnian rocks are unweathered beneath the unconformity, which shows sharp irregularities indicating that erosion had preferentially picked out subvertical joints in the Precambrian basement. The Triassic strata evidently accumulated within a shallow depression and are observed to progressively overstep the basement rocks in an eastwards direction, feathering out against the base of Morley Hill. This relationship shows that the hill existed in Triassic times, and therefore represents part of an exhumed palaeo-topography. The lowermost Triassic bed consists of 1 to 2 m of poorly sorted breccia made up of angular Charnian rock fragments within a red, silty sandstone matrix. The high matrix content suggests that these beds may be accumulations of finer-grained material, ultimately derived from arid weathering processes and possibly washed in by ephemeral sheetfloods or debris flows; there is a relatively small input from rockfalls, represented by the Charnian fragments.

Along the top of the quarry face, the Triassic rocks are overlain by 1-2 m of head, a Quaternary deposit that locally consists of abundant angular Charnian fragments in a pale brown, sandy or silty matrix. The head extends eastwards, up the slope and on to Morley Hill, overlying both the Triassic and Precambrian bedrock. On the hill itself , the angular blocks are closely packed, and the deposit resembles a scree that perhaps was formed by freeze-thaw activity in a cold Devensian climate, before the hill became fully covered by vegetation.

References

Carney, J. N., 1994. Geology of the Thringstone, Shepshed and Loughborough districts (SK41NW, SK41NE and SK51NW). *British Geological Survey Technical Report* WA/94/08.

Lowe, D. R., 1982. Sediment gravity flows: II, depositional models with special reference to the deposits of high-density turbidity currents. *Journal of Sedimentary Petrology*, **52**, 279-297.

Moseley, J. B. and Ford, T. D., 1989. The sedimentology of the Charnian Supergroup. *Mercian Geologist*, **11**, 251-274.

Pharaoh, T. C. and Evans, C. J., 1987. Morley Quarry No.1 Borehole: Geological Well Completion Report. Investigation of the Geothermal Potential of the UK, *British Geological Survey Report*. 43 pp.

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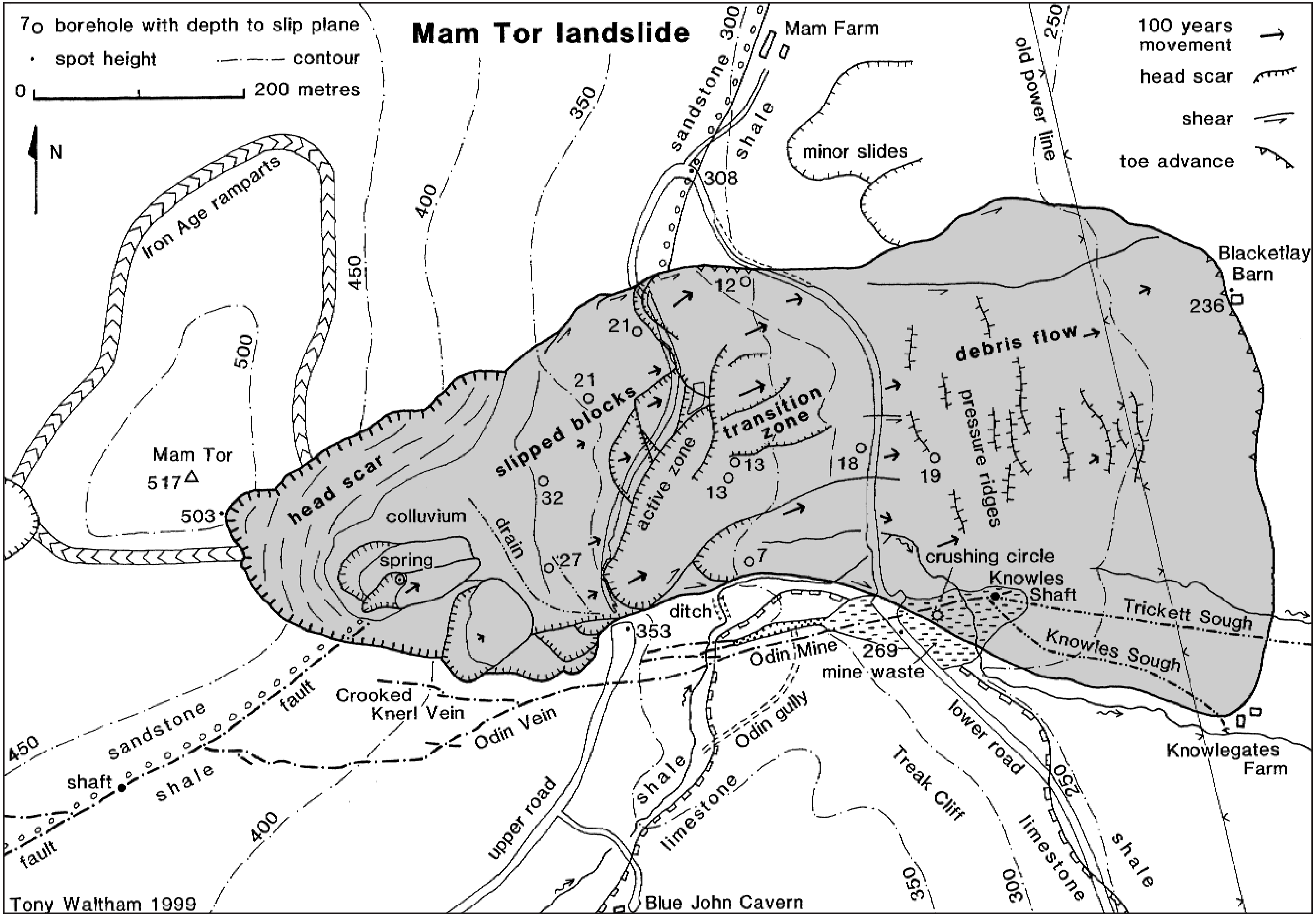

Figure 1. Map of the Mam Tor landslide with arrows drawn to lengths that represent 100 years of ground movement on the map scale.

REPORT

Landslide movement at Mam Tor

The Mam Tor landslide is just one of the features that make the Castleton area of the Peak District a popular destination for geologists. Initial failure of the shale and sandstone slope occurred over 4000 years ago as a rotational landslide that developed into a large debris flow at its toe. The road that was built across it nearly 200 years ago (and was closed in 1979) provides graphic evidence of movement of the slide mass, and the site is now a classic for teaching slope processes and engineering geology.

Surveying students in the Civil Engineering Department of Nottingham Trent University used the site as a class exercise for eight years. They established a series of over 50 fixed stations that were resurveyed each year, and the results have provided a record of the slide's movement, as told in a paper just published (Waltham, A.C. & Dixon, N, 2000. Movement of the Mam Tor landslide, Derbyshire. *Quarterly Journal of Engineering Geology and Hydrogeology*, **33**, 105-123).

The active landslide contains over 3.2M m^3 of slipped material. It is 1000 m long, with a fall of 270 m below a head scar 70 m high, and three structural zones have now been recognised within the slide mass. The upper part (above the upper road) is a series of rock slices that were produced by the rotational failure of the original slope, and most of these slices have little movement today. The lower part (crossed by the lower road) is a debris flow of broken slide material that continues to slide over a basal shear surface. Between these, a central zone is an unstable complex of blocks and slices that overlie the steepest part of the landslide's basal shear and are disintegrating into debris as they are deformed; this part of the slide has the most rapid movement. The upper road is broken where it crosses the head scars of these active slide blocks, while the lower road is merely deformed into waves by the plastic movement of its underlying debris flow.

Figure 1 shows the different rates of movement across the landslide; the length of each arrow is drawn to the map scale to indicate 100 years of movement (details on derivation of the data are in the QJEGH paper). The current mean annual movement is up to 0.25 m, but this is not at a steady rate. Nearly all the movement occurs through the winter months, and is significantly increased in wet years. Movements do not increase in proportion to rainfalls and consequent groundwater levels, but instead increase dramatically when threshold levels are exceeded. When rainfall in a winter month exceeds 210 mm after at least 750 mm of rain in the preceding six months, parts of the slide move more than half a metre (mostly within the wet month), but drier years have only 10% of the wet year movement. These rainfall thresholds are exceeded once in every four years, and movement predictions can now be made. Trent University's work at Mam Tor finished in 1998, but monitoring is being continued by Manchester University; they had already started with two dry and unexciting winters, but 1998/9 was wet - when they recorded their first large movements, in line with predictions.

Recognition of the patterns of movement at Mam Tor has improved understanding of the landslide's evolution. Figure 2a shows the original slope where an unbuttressed wedge of shale stood in front of a mass of sandstone; this probably failed (Fig. 2b) as a precursor to the main slide event. The main rotational landslide is likely to have been a single large event (Fig. 2c), when a mass of rock moved rapidly over a new slip surface along which strength was reduced as it sheared. From the initial rotational failure, the toe of the landslide blocks has broken into a debris mass that has continued to flow down the slope (Fig. 2d). Renewed failure of the head scar will occur when the existing slide blocks have slumped and been eroded enough to reduce support at the foot of the shale slope (Fig. 2e); the almost stable nature of the upper blocks implies that this is not imminent.

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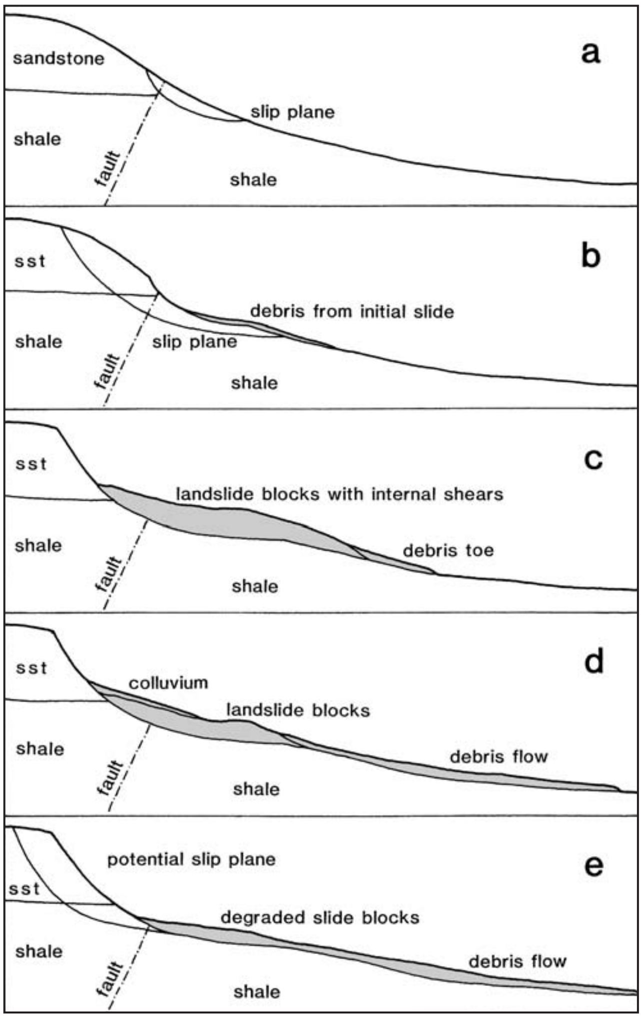


Figure 2. Evolution stages of the Mam Tor landslide.

REPORT

John Muir

We had stopped to view the pillow lavas and columnar jointing at Dunbar, when I spied *John Muir Birthplace* in the High Street. “Who’s John Muir?” I murmured, and Alan remembered the Muir Woods near San Francisco. Visits to Muir’s birthplace and *An infinite storm of beauty – the Life and Achievements of John Muir* the City Art Centre in Edinburgh inspired us to learn more.

When John Muir was born in 1838, geology was not regarded as a separate science and “Noah’s flood” was held to be responsible for much of the way the Earth looked. In the 1820s and 1830s the work of men like James Hutton became accepted, and in the 1840s Charles Lyell and Louis Agassiz influenced contemporary ideas following successful lecture tours in America.

In 1870 Muir guided geologist Joseph Le Comte around the Yosemite Valley in California, and pointed out evidence of glacial action that supported Agissez’s theories. In the following year, the New York Tribune published John Muir’s first article, on the subject of glaciers. Despite his geological successes, John Muir is better known to many EMGS members for his role in preserving for posterity many of the geological sites that they have visited.

Thanks to John Muir, Yosemite became part of the surrounding National Park in 1891, some 19 years after Yellowstone had become the first designated national park in the USA. Following further work by Muir, Mt Rainier became a National Park in 1899, as did Petrified Forest in 1906; Grand Canyon National Park and Muir Woods National Monument were established in 1908. Society members who have visited Alaska will be aware that in 1879, on his first trip north, Muir entered Glacier Bay as far as the glacier that was later named after him.

Muir’s interests encompassed all the natural world. On a youthful journey home from university he noted 200 flowering plants along one 200-yard stretch of an Illinois trail. He was an enthusiastic climber, and made the first ascent of Mount Ritter in 1872 and the first recorded ascent of Mount Whitney’s eastern route the next year.

Perhaps John Muir’s respect for the natural world developed in Dunbar, where he was third of seven children. He started school at the age of three, and later progressed to Dunbar Grammar School where he included geography in his studies. John’s father, Daniel Muir, was a member of the Disciples of Christ sect, which led to Daniel and the three elder children emigrating to Wisconsin in 1849, the year of the Californian Gold Rush. After only a few months they were sufficiently established to send for Mrs Muir and the rest of the children.

Through the 1850s John worked on the farm. Daniel Muir opposed his son’s attempts at learning; to his mind a knowledge of scripture and religious writing was all that anyone needed. John cut down his hours of sleep to give him time to learn maths, geography, literature and philosophy and read Hugh Miller’s *In the Footsteps of the Creator*. He was fortunate that neighbouring farmers, fellow Scots, were willing to supply books and encouragement.

He constructed clocks and barometers and contrived inventions, which he exhibited at the 1860 State Fair in Madison, where he accepted an offer to work in a machine shop in return for instruction in mechanical drawing. In lodgings he met students who were admitted to the University of Wisconsin for one dollar per week. Despite his scrappy early schooling, Muir studied chemistry, natural history and geology and first encountered the ideas of Agissez, Lyell and Huxley.

John Muir spent three years at the university, returning to the farm to help with the harvest each summer. Meantime North and South were heading towards war. Wisconsin was alive with recruiting agents, and many farm boys volunteered to serve in the army to escape the boredom of farm life. In March 1864 Congress passed the Enrollment (sic) Act requiring males of 18-45 years , who were American citizens or "aliens wishing to become such", to enrol for military service. Those who dodged the draft by leaving to work elsewhere were said to have "skedaddled"; John and his brother Daniel "skedaddled" to Canada. John studied plants around Niagara Falls, and worked with Daniel in a broom factory.

After the war John Muir returned to the USA to work as a foreman-engineer in a carriage factory in Indianapolis, then the great Railway City of America. While adjusting a machine he was injured in the right eye, and his sight would never again be perfect. He set off with a friend to walk through Illinois to Wisconsin, where he spent the rest of the summer with his family. From Wisconsin he walked 1600 km to Florida via Kentucky, North Carolina and Georgia. After a bout of malaria, he took a ship for New York, and then sailed to Panama, crossed the isthmus by railroad and went on by boat to San Francisco.

The 30-year-old Muir chose the quickest route out of town, making for Yosemite through wheat fields, orchards and alfalfa meadows. From the top of the Pacheco Pass he saw for the first time the Sierras, 150 km away. During eight days in Yosemite Muir sketched, explored the waterfalls, collected flowers and saw his first sequoias. To keep himself he broke horses, manned a ferry and sheared sheep, but continued his botany studies, noting 550 mosses in an area measured in inches.

After the wet winter of 1869, John Muir explored the mountains, having undertaken to move sheep there, and in August he made the first ascent of Cathedral Peak above the Yosemite Valley. So began his ten "Yosemite Years" during which he was camped out among the sequoias of the Mariposa Grove, that were preserved for posterity by his efforts. The next few years read like a Boys' Own adventure, establishing the pattern which he followed for the rest of his life, spending winters in "civilisation" and summers exploring the wilderness.

Summer 1877 saw John visiting friends in San Francisco, where he met the Polish emigrant Dr John Strentzel and his American wife, Louisiana. Their daughter, Louie Wanda, was destined to be a concert pianist, until she married Muir in 1880.

In 1895 Muir was at last able to re-visit Dunbar and Edinburgh, before moving on to London and through Europe. He followed in 1903-4 with a world tour through London, Paris, Russia, Korea, Japan, China, India, Egypt, Australasia, Malaya, Philippines, Hong Kong and Hawaii.

Returning home, Muir took his daughter Helen, then recovering from pneumonia, to the Arizona desert, where she had been advised to live for a year to strengthen her lungs. He was summoned home by the news that his wife Louie was gravely ill, and she died of lung cancer a month later. Despite long periods spent apart, it had been a happy marriage.

John Muir spent time with his convalescent daughter at the Petrified Forest, where he realised that the serious-minded visitors were followed by despoilers who dynamited the logs to sell the pieces of agate. Muir threw himself into the fray and made a study of the Petrified Forest, that led to the site being made a National Park the following year. He continued to campaign to protect wilderness areas until, in that watershed year of 1914, he died in Los Angeles.

But that is not the end of the story. The American National Parks where John Muir worked were joined in 1974 by the John Muir Country Park in Scotland, a protected area of unspoilt coastline around Dunbar. In the same town, his birthplace opened to the public in 1980.

"When we contemplate the whole globe as one great dewdrop, striped and dotted with continents and islands, flying through space with all the other stars, all singing and shining together as one, the whole universe appears as an infinite storm of beauty." This poetic vision of our universe has a surprisingly modern feel, but it was written by John Muir in The Story of My Boyhood and Youth, published in 1913. His other books include The Mountains of California (1894), Our National Parks (1901), Stickeen (1909), My First Summer in the Sierra (1911) and The Story of my Boyhood and Youth (1913).

On his death in 1914 John Muir was elevated to the status of a "Father of the American National Parks", along with Ralph Emerson, Henry Thoreau and John Audubon.

Pauline Dawn
Stamford & District Geological Society

Yosemite Valley, with Half Dome in profile on the left, seen from the top of Cloud's Rest.

REPORT

Titan Shaft, Peak Cavern

Peak Cavern is the finest of the cave systems beneath Derbyshire's White Peak, and more than 15 km of passages have been mapped in its complex series of streamways, shafts and chambers. It has yielded its secrets slowly, because explorations have been hindered by deep flooded loop passages and major collapsed boulder chokes. Weekend cavers continue to find new bits, and have now found the largest and deepest shaft in Britain.

The Titan Shaft was entered at its base when cavers dug their way up through a great pile of fallen limestone blocks on New Year's Day 1999. They had started in a choke at the side of the main stream passage nearly 2 km in from Peak Cavern's gaping entrance, and were nearly 30 m above water level when they came out into a chamber with its walls soaring into blackness. The only way up Titan was by climbing the walls - mostly by placing a line of rockbolts in the smooth water-polished limestone. This took many weekends of long trips underground, but six months after finding the floor of Titan, they reached its top, 145 m above its floor.

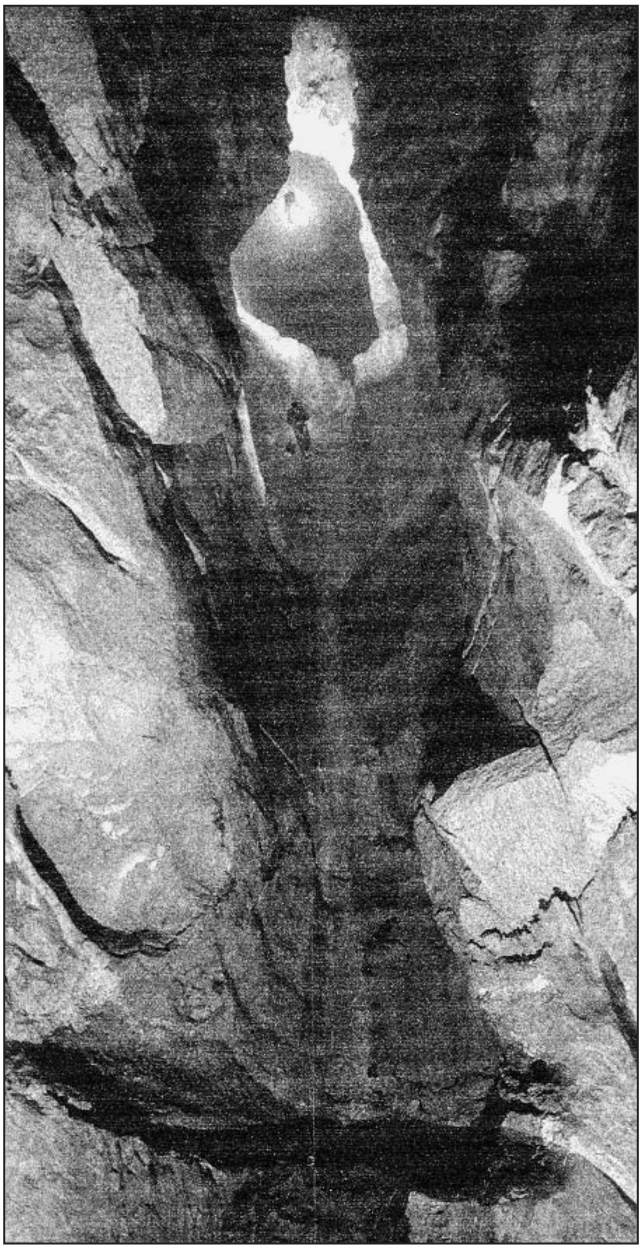
Titan is a truly massive shaft. Its lower half is about 10 by 20 m in plan; it narrows at some rock overhangs about 60 m up. The upper half of the shaft is a huge rift about 15 m wide and opening upwards to about 80 m long at its main bedding plane roof. A small stream enters from an inlet cave at mid-height, and becomes a narrow waterfall 60 m high, but Titan's upper rift is almost dry. Titan is by far the deepest shaft in Britain; Ingleborough's Gaping Gill is just 110 m deep

Titan lies beneath the grass slopes of Hurd Low, between Rowter Farm and the top end of Cave Dale, where the land surface is almost exactly 200 m above the Peak Cavern stream passage. It has been formed on a narrow lead vein that lies almost east-west. Miners of the past had worked this to just a few metres depth. Perhaps it was fortunate that the vein was not rich enough to entice them deeper – where they could have broken into the top of Titan, with traumatic consequences.

It appears that Titan originated as one of the large vein cavities that characterise the Peak Ditrict karst. These were etched out by dissolution along the existing rock joints, and their origins appear to reach back to hydrothermal processes linked to deposition of the vein minerals. Subsequent dissolution was by karstic circulation of meteoric waters, far below the water table, and long before fluvial excavation of the Hope Valley had allowed drainage of the limestone. Water from the surface never entered directly into Titan; a large choked passage in the western end of the rift 120 m above the floor may be the remains of an important cave that fed drainage from the west into the shaft.

For much of the Pleistocene, drainage from Rushup Edge looped deep into the limestone before emerging from Peak Cavern into a Hope Valley whose floor was far above that of today. That original rising was a deep vauclusian spring, which was drained when its outflow channel was cut down (to create the Peak Cavern gorge) in response to the valley floor lowering. Titan was progressively emptied as the water table fell, and the shaft continued to be enlarged and modified by waterfall dissolution and small-scale rock collapse. Ultimately, surface lowering will expose its top, permit greater erosion of its walls, and let more rock fall to its floor - until it looks more like Eldon Hole. But today, Titan remains in the dark, as a deeply hidden gem of the Peak District geology.

Tony Waltham



Cavers on a single rope give scale to the lower half of Titan shaft [Photo: Paul Deakin]

PRESIDENTIAL ADDRESS

A new glacial stratigraphy for 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.

When I started to plan three Presidential Addresses for the Society, I decided to leave East Anglia until last, as new information was appearing all the time. Of course as time went on this new information became more and more difficult to interpret! Fortunately we were able to "cut the gordian knot" during our 1999 fieldwork and I am now in a position to put forward a completely new interpretation of the pre-Devensian glacial sequences of East Anglia, and particularly northeastern Norfolk.

I have been working in East Anglia since 1991, on a mapping project led by Brian Moorlock. There have been four people in the team throughout, other members at various times being Steve Booth, Tony Morigi, Dennis Jeffery, Mike Smith and Holger Kessler. I must also mention Profesor 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. We started in Suffolk and worked northward, deliberately leaving the difficult Cromer sheet until last, and it is in the mapping of this last sheet that the glacial stratigraphy has finally been resolved.

The sequence of tills

In recent years it has come to be accepted that all the pre-Devensian glacial deposits of East Anglia are Anglian in age, and these have been divided into two formations, most recently termed the North Sea Drift Formation and Lowestoft Formation (Bowen *et al.*, 1999). These are derived from two distinct ice sheets, the ‘Scandinavian Ice Sheet’, which entered the area from the north or north-north-east, and the ‘British Eastern Ice Sheet’, which entered from the west. In general it can be said that the deposits of the North Sea Drift Formation are derived from the former ice sheet, since they are characterised by a suite of igneous and metamorphic erratics from the Olslofjord region, while the deposits of the Lowestoft Formation are derived from the latter ice sheet, and contain erratics derived from the Mesozoic outcrops to the northwest, principally the Chalk and Kimmeridge Clay. However, it has generally been believed that the two ice sheets co-existed (Hart and Boulton, 1991).

In northeast Norfolk, three tills were recognised within the North Sea Drift (Table 1; Banham, 1968, 1988), of which the middle one was noticeably more calcareous than the others. The Lowestoft Formation in the area was termed "Marly Drift" as it was formed almost wholly of reconstituted Chalk. During the late 1980s and early 1990s, Jane Hart and Juha Pekka Lunkka worked on the coast sections as part of their PhD studies (Hart and Boulton, 1991; Lunkka 1994). Unfortunately, in view of the contorted nature of the deposits, they were unable to agree on the stratigraphy, but I believe that I have correctly correlated their respective nomenclatures with that of Banham in Table 1.

When the BGS team set out to re-survey the Cromer sheet we were not anticipating erecting a new stratigraphy; we started at the western end of the area where we believed the deposits would be least contorted, and assumed that as we worked eastward, we would move off the Lowestoft Till onto the lower formation. However, this was not to be the case – as we crossed the area, the Lowestoft Till passed beneath gravels which we found to be associated with the Third Cromer Till. Furthermore, study of boreholes across the eastern part of the sheet demonstrated that the Lowestoft Till appeared to pass eastward into the Second Cromer Till. Comparison of the lithologies and provenance of the Lowestoft and Second Cromer tills subsequently confirmed that they were indeed the same unit, and we realised that there are in fact only three major tills in the succession, not the four shown in Table 1. Our new proposed stratigraphy is shown in Table 2: the First, Second and Third Cromer tills become the Happisburgh, Walcott and Hanworth till members of the Corton, Lowestoft and Overstrand formations.

The present account will largely consider the till members - there are also complex sequences of related sands, gravels and lacustrine clays related to each till member. Now that the relationships of the deposits are understood, we are better able to identify individual tills in the field, and we can say more about the sedimentology and provenance of each of them.

Table 1. Pre-Devensian stratigraphic sequences of northeastern Norfolk according to Banham, Hart and Lunkka.

Banham (1968, 1988)	Hart and Boulton (1991)	Lunkka (1994)a
Lowestoft Till = Marly Drift		Lowestoft Till Formation, Marly Drift Member
Third Cromer Till	Walcott Diamicton Member	Cromer Diamicton Member, Mundesley Diamicton Member
Second Cromer Till	Eccles Diamicton Member	Walcott Diamicton Member
First Cromer Till	Happisburgh Diamicton Member	Happisburgh Diamicton Member

Overstrand Formation	Hanworth Till Member
Lowestoft Formation	Walcott Till Member
Corton Formation	Happisburgh Till Member

Table 2. A new stratigraphy for the pre-Devensian tills of northeast Norfolk. Only the names of the formations and till members are shown; outwash sands and gravels and lacustrine deposits also occur within each of the three formations.

The three till sheets

The oldest, the Happisburgh Till, is a massive sandy till, reddish brown weathering pale yellow in colour, and generally 3-5m thick. It includes both lodgement and waterlain tills, and is poor in both carbonate (<2%) and megaclasts (most clasts <32mm). The clasts are dominantly flint, vein quartz and quartzite, but include Scandinavian rhomb porphyries, mica schists, gneiss and granitic rocks. The source of most of the material is clearly the North Sea and Scandinavia. However, examination of the derived micropalaeontology of the till by our colleague Jim Riding proved interesting. Jurassic palynomorphs were rare, arguing against the contemporary presence of the British Eastern Ice Sheet, but Carboniferous spores were extremely common, including a definite Westphalian input. There are no Carboniferous outcrops between Norway and Norfolk, and secondary derivation via the North Sea is unlikely as this would be accompanied by a varied asemblage including Jurassic forms. Consequently the only source would be northeastern Britain: either the ice sheet touched the shores of northeastern Britain before swinging south to Norfolk, or it was joined by a tributary glacier from that direction.

The Walcott Till is a stiff blue-grey chalky flinty till, which compared to the Happisburgh Till has higher clay and silt content, lower sand content, and more opaque heavy minerals. It contains 23-43% of carbonate (Lunkka, 1994), as does the Lowestoft Till in its main outcrop (Perrin et al., 1979). It is megaclast-rich, dominated by chalk clasts but also including angular flint and Jurassic limestone, mudstone and fossils, and a little quartzite and vein quartz. The micropalaeontology is dominated by spores of Carboniferous (Visean to Westphalian) and Jurassic (mainly Kimmeridgian) age. Clearly the source is eastern Britain, with little if any input from the North Sea and none from either Scandinavia or Scotland.

The Hanworth Till is a massive, very sandy till with the same Scandinavian and North Sea provenance as the Happisburgh Till, but overall it contains more megaclasts, with rounded flints and Scandinavian erratics commonly larger than 10cm. It varies in thickness more than does the Happisburgh Till, ranging up to more than 10m thick, and unlike the Happisburgh Till, it locally includes large quantities of very local Chalk. This may be in the form of rafts of pure Chalk, or else as ground-up, reconstituted chalk or "Marly Drift". It was this marly drift within the Overstrand Formation which in the past has been mistaken for Lowestoft Till, leading to the mistaken conclusion that the Lowestoft Formation overlay the North Sea Drift. During the Society's visit in 1995, rafts of Chalk up to more than 500m long were seen in the cliffs at West Runton.

The famous "contorted drift" of the northeast Norfolk coast (Reid, 1882; Hart and Boulton, 1991; Hart and Roberts 1994), formed by isoclinal folding within the till as a result of very high pore water pressures maintaining the till in an almost liquid state, is restricted to the Hanworth Till on the coast. Farther south it is a massive, undeformed till. Thrusting is also associated with the Overstrand Formation, and particularly fine thrusts were seen at Sidestrand on the Society's visit. Indeed it appears that the Happisburgh and Walcott tills are always massive and only deformed by horizontal shearing, while the "contorted drift", thrusting and formation of large rafts of Chalk are restricted to the Hanworth Till Member.

The glacial chronology

Traditionally the North Sea Drift and Lowestoft formations were both considered to be Anglian in age, and were therefore assigned to Oxygen Isotope Stage 12 [OIS 12] (Bowen *et al.* 1999). However, our new stratigraphy yields little support for the assumption that the Scandinavian and British Eastern ice sheets co-existed, and the possibility must be considered that the three formations now proposed may relate to chronologically separate ice advances.

The Lowestoft Formation does appear to be significantly younger than the Corton Formation. There is a strong unconformity between them, with the Lowestoft Formation resting on a deeply eroded topography cut in the Corton Formation in southeast Norfolk. The Lowestoft/Walcott till is much less weathered than the Happisburgh Till, which weathers to form the "Norwich Brickearth" (Rose et al. 1999). Also the Lowestoft Till incorporates clasts of calcrete derived from the underlying Corton Formation (Hopson and Bridge 1987), implying a sufficient time gap between the two formations to allow calcrete to form within the Corton Formation. The Overstrand Formation also appears to be significantly younger than the Lowestoft Formation: it rests upon a deeply eroded topography cut in the Lowestoft Formation, and it shows examples of "constructional geomorpholgy". That is to say, there are landforms associated with the Overstrand Formation which reflect the construction or deposition of the deposits, rather than their erosion. These include the Cromer Ridge, a gravel ridge over 100m high formed at the proximal end of a major sandur, the Blakeney Esker

A large raft of Upper Chalk within chalk-rich "Contorted Drift" of the Hanworth Till (Overstrand Formation) exposed in the sea cliffs at West Runton.

(visited by the Society in 1995), and a series of kames in the Glaven Valley, southeast of the Blakeney Esker.

The freshness of the Overstrand Formation and its associated geomorphological features imply that it is younger than Anglian, as such constructional features are not normally associated with the British Anglian deposits, either in East Anglia or the Midlands. However it is not likely to be Devensian, as it is entirely unlike the Devensian Holderness Formation which can be seen in Norfolk between Hunstanton and Morston, west of Blakeney. It thus corresponds to the intervening "Wolstonian" glaciation, correlating with the Saalian in the Netherlands and Germany. This is now ascribed to OIS 6, and glacial deposits of this age are now recognised in several areas of Eastern England. These include the gravels and tills of the Welton-le-Wold Formation in Lincolnshire (Bowen *et al.*, 1986), the Basement Till at Bridlington (Catt, 1991), and the outwash gravels of the Tottenhill member of the Nar Valley Formation in Norfolk (Gibbard *et al.*, 1991, 1992, Lewis & Rose, 1991). Since this was a major glaciation in the Netherlands, it would be expected that a major suite of glacigenic deposits would be found in Norfolk.

The Corton and Lowestoft formations would be ascribed to the "Anglian" Glaciation, but although this is ascribed to OIS 12 by Bowen *et al.* (1999), there is increasing evidence that it includes at least two distinct glaciations. Mike Sumbler's work on the terraces of the rivers Thames and Thame implies that glaciations occurred in the Midlands in both OIS 10 and 12 (Sumbler, 1995), and Alan Brandon's work on the Trent supports this (Foster *et al.*, 1999). In East Anglia, Uranium/Thorium dating on interglacial deposits from Tottenhill, Norfolk (Rowe *et al.*, 1997) and from Marks Tey, Essex (Rowe *et al.*, 1999) respectively imply glaciations during stages 10 and 12. It is thus tempting to date the Corton and Lowestoft formations as OIS 12 and 10 respectively. However, the Tottenhill and Marks Tey tills are both of the Lowestoft type, unlike the Happisburgh till in northeast Norfolk. Also Sumbler (1995) indicates that it was the earlier (OIS 12) glaciation which diverted the river Thames, and hence was a more far-travelled glaciation than that in OIS 10, whereas in northeast Norfolk, it appears that the Walcott Till extended farther south, with the Corton Formation being relatively local. Thus an alternative possibility is that the Walcott Till/Lowestoft Formation in north-east Norfolk relates to OIS 12, and the Corton Formation to an earlier cold period, perhaps OIS 14. However, the possibility still remains that both formations date from OIS 12, possibly separated by an interstadial. The dating of the Corton Formation may soon be constrained by work on small mammals in the "Unio Bed" underlying the Happisburgh Till at Sidestrand (Preece and Parfitt, 2000), but it is difficult to see how the age of the Walcott Till can be finally confirmed as OIS 10 or 12 unless further interglacial sites are found to constrain it.

References

Banham, P.H. 1968. A preliminary note on the Pleistocene stratigraphy of north-east Norfolk. *Proceedings of the Geologists' Association*, 79, 281-285.

Banham, P.H. 1988. Polyphase glaciotectonic deformation in the Contorted Drift of Norfolk. 27-32 in: Croot, D.G., editor, *Glaciotectonics; Forms and Processes*. Balkema, Rotterdam.

Bowen, D.Q, editor. 1999. A revised correlation of Quaternary deposits in the British Isles. *Geol. Soc. Special Report No 23*.

Bowen, D.Q., Rose, J., McCabe, A.M. and Sutherland, D.G. 1986. Quaternary Glaciations in England, Ireland Scotland and Wales. *Quaternary Science Reviews*, 5, 299-340.

Catt, J.A., 1991. Late Devensian glacial deposits and glaciations in eastern England and the adjoining offshore region. In: Ehlers, J., Gibbard, P.L. and Rose, J., editors: *Glacial deposits in Britain and Ireland*. Balkema, Rotterdam.

Foster, S.S.D., Morigi, A.N. and Browne, M.A.E. 1999. *Quaternary geology – towards meeting user requirements*. British Geological Survey, Keyworth, Nottingham.

Gibbard, P.L., West, R.G., Andrew, R. and Petitt, M. 1991. Tottenhill, Norfolk. 131-143 in: Lewis, S.G., Whiteman, C.A. and Bridgland, D.R., editors, *Central East Anglia and the Fen Basin. Field Guide*. Quaternary Research Association, London.

Gibbard, P.L., West, R.G., Andrew, R. and Petitt, M. 1992. The margins of a Middle Pleistocene ice advance at Totenhill, Norfolk, England. *Geological Magazine*, 129, 59-76.

Hart, J.K. and Boulton, G.S. 1991. *The glacial drifts of north-eastern Norfolk*. 233-243 in: Ehlers, J., Gibbard, P.L. & Rose, J., eds: Glacial deposits in Britain and Ireland. Balkema.

Hart, J.K and Roberts, D.H. 1994. Criteria to distinguish between subglacial glaciotectonic and glaciomarine sedimentation, I: Deformation styles and sedimentology. *Sedimentary Geology*, 91, 191-213.

Hopson, P.M. and Bridge, D.McC. 1987. Middle Pleistocene stratigraphy in the lower Waveney Valley, East Anglia. *Proceedings of the Geologists' Association*, 98, 171-185.

Lewis, S.G. and Rose, J.1991. Tottenhill, Norfolk. 145-148 in: Lewis, S.G., Whiteman, C.A. and Bridgland, D.R., editors, *Central East Anglia and the Fen Basin. Field Guide*. Quaternary Research Association, London.

Lunkka, J.P. 1994. Sedimentation and lithostratigraphy of the North Sea Drift and Lowestoft Till Formations in the coastal cliffs of NE Norfolk, England. *Journ. Quat. Sci.*, 9, 209-234.

Perrin, R.M.S., Rose, J. and Davies, H. 1979. The distribution, variation and origins of pre-Devensian tills in eastern England. *Phil. Trans. Roy. Soc., Series B*, 287, 535-570.

Preece, R.C. and Parfitt, S.A., 2000. 1-28 in Lewis, S.G., Whiteman, C.A. and Preece, R.C., editors, *The Quaternary of Norfolk and Suffolk: Field Guide*. Quat. Res. Assoc., London.

Reid, C. 1882. The geology of the country around Cromer (Sheet 68E). *Memoirs of the Geological Survey, England and Wales*.

Rose, J., Lee, J.A., Moorlock, B.S.P and Hamblin, R.J.O. 1999. The origin of the Norwich Brickearth: micromorphological evidence for pedological alteration of sandy Anglian Till in northeast Norfolk. *Proc. Geol. Assoc.*, 110, 1-8.

Rowe, P.J., Atkinson, T.C. and Turner, C. 1999. U-series dating of Hoxnian interglacial deposits at Marks Tey, Essex, England. *Journal of Quaternary Science*, 14, 693-702.

Rowe, P.J., Richards, D.A., Atkinson, T.C., Bottrell, S.H. and Cliff, R.A., 1997. Geochemistry and radiometric dating of a Middle Pleistocene peat. *Geochimica et Cosmochimica Acta*, 61, 4201-4211.

Sumbler, M.G. 1995. The terraces of the rivers Thame and Thames and their bearing on the chronology of glaciation in central and eastern England. *Proceedings of the Geologists' Association*, 106, 93-106.

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REPORT

How the Mediterranean dried up

Summary of lecture presented to the Society on Saturday 4th December 1999 by Dr Rob Butler, of Leeds University.

The Salinity Crisis in the Mediterranean represents one of the most dramatic examples environmental change outside of glaciated areas in the relatively young geological record. In the 1970s, deep sea drilling confirmed that sediments beneath the floor of the Mediterranean included a layer of salt. For these researchers, the salt layer, sandwiched between sediments that had been deposited under very deep water conditions, implied one thing: the Mediterranean had once dried up. It was well known from plate reconstructions that Africa and Europe had moved together to isolate what was once the open Tethys ocean into the restricted Mediterranean by the end of Miocene times (the Messinian stage, about 7-5 million years ago). The isolation was completed by a sea-level fall of world-wide extent (linked to a resurgence in glaciation) that cut off the Mediterranean from the Atlantic. The isolated sea was then thought to have dried out, only filling when the world sea-level rose again during global warming at the start of Pliocene times. Rough calculations indicate that, with no river input, an isolated Mediterranean would evaporate in a few tens of thousands of years, given the arid climates that characterise glacial maximums. Refilling by the Atlantic pouring back in through a breached Gates of Gibraltar might take a little longer.

Evaporites in Sicily

Central to the development of these dramatic models were the on-land outcrops of Miocene strata on the island of Sicily. Messinian halite and potash salts, together with gypsum, had long been exploited commercially from more than 800m of salt thickness in some basins. These deposits are classically separated into two cycles separated by a sub-aerial unconformity. The First Cycle includes chloride salts and organic-rich facies while the Second Cycle contains clastic evaporites and gypsum. Linked structural and stratigraphic studies in central and southern Sicily show that the evaporites accumulated in synclines related to underlying thrust structures of the frontal part of the Maghrebian orogenic belt. This orogen runs through north Africa (geologically, southeastern Sicily is part of the African foreland) and links into the southern Apennines of Italy. Prior to the Salinity Crisis these basins were hydrodynamically linked through the foredeep to the Mediterranean.

The precursor sediments, of the Terravecchia Formation, formed a delta, sourced from the north.

The crests of anticlines have late Tortonian to early Messinian patch reefs upon them. The synclines that host the Mesinian evaporites formed a tiered system, with originally shallow water in the north to progressively deeper water in the south. Thus Sicily provides an ideal 'tide gauge' for charting how the level of the Mediterranean sea fell during the Messinian. The prediction is that the northern synclines experienced more restricted sea water circulation, while those in the south were submerged beneath open water. Consequently the first evaporites should form in the north, getting progressively younger to the south (Fig. 1).

The evaporite facies vary over very short distances across the Sicilian folds. Anticline crest show evaporitic carbonates with lime muds and local sabbkha-like textures. In general these successions are about 10m thick and show bed-by-bed brecciation and collapse. These features suggest that sea level was oscillating, leaving anticline crests sometimes a few metres below sea level and at other times exposed to rainfall and karstification. In contrast, mine data show that the synclines locally contain over 500m, of halite and potash salts. The flanks of the folds commonly contain gypsum. Thus the evaporitic facies are fractionated, depending on their structural position. The simple explanation is that outlying anticlines act as a porous barrier within which the less soluble salts accumulate, leaving water enriched in the more soluble halite and potash salts to pass into the syncline where they are deposited. Structural architecture and evolution of the Messinian basins on Sicily exerts a fundamental control on the stratigraphy. Thrusting provides accommodation space for evaporites and also controls the water pathways into the desiccating basins.

Mine and outcrop data show that the Messinian evaporites contain an important inter-regional unconformity. This surface separating First and Second Cycle evaporites is related to the forced regression associated with the acme of Mediterranean desiccation, an interpretation supported by local ravinement and incised valley fills. The overlying Second Cycle evaporites are a combination of detrital, reworked First Cycle material and primary gypsum formed under brackish water. Regional onlap relationships and bed continuity suggest that this water body was of regional extent, with a systematically rising baselevel. The Second Cycle evaporites mark the replenishment of baselevel to near normal sea levels. However, normal sea water conditions, as charted by a rich fauna, only occurs later, at the onset of the Pliocene. These younger strata are typically chalks (the Trubi Formation) that show regional transgressive behaviour on substrata.

Establishing the chronology

By linking tectonic and sequence stratigraphic analyses to facies distributions across the Sicilian basins it is possible to build up a picture of sea level variations and climatic fluctuations. However, the absolute timing of these events and the rates of the processes requires additional data. As part of a regional study of deformation rates (The Central Sicily Basins Project), high resolution stratigraphic data were collected. For these types of problems, traditional fossil studies are of little use, as they rarely provide adequate temporal resolution and are environmentally sensitive; not much lives in the saline world of a halite basin. So our approach relies on linking magneto-stratigraphy to depositional cyclo-stratigraphies. Sediments can record reversals

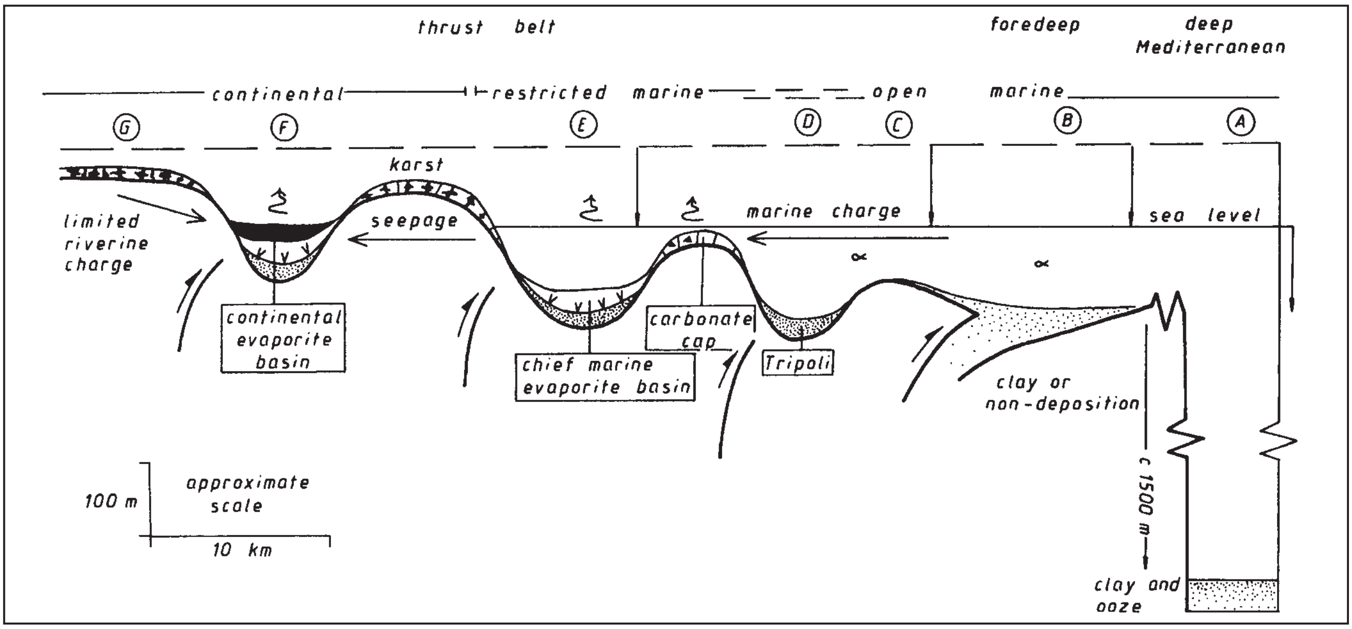


Figure 1. The model for evaporite accumulation in the synclines across Sicily, shown schematically. The sites range from north (G to the left) to south (C to the right) across the thrust belt. A continued fall in sea level will desicate basin D, and leave basin C in a continental environment. The model predicts diachroneity (Butler et al, 1995).

in the polarity of the Earth's magnetic field (rather like ocean floor magnetic anomalies chart sea-floor spreading). However, to calibrate reversals in measured sections with the world-wide reversal record requires additional controls. We use the fact that reversals represent different periods of time. Neogene marine sediments in the Mediterranean commonly show cyclic variations that have been matched to regular fluctations in earth orbit. These precession cycles have a period of about 24,000 years. Consequently by counting cycles we can sum the duration of time and calibrate the duration of our measured magneto-stratigraphic section. This can then be matched to the global record (Fig. 2). Potentially, the method can give a temporal resolution of a single precession cycle (24,000 years) even for sediments several million years old.

Our results from a range of sites across Sicily show that the onset of evaporite accumulation was diachronous. Calibrating the magnetostratigraphy shows that the fall of Mediterranean sea level was protracted. The earliest evaporites in our study accumulated early in chron C3Ar (pre 6.88 Ma) and the youngest accumulated late in chron C3An (post 6.0 Ma). During this period the basinward (southward) shift in coastline was 70 km and in vertical section implies a relative fall in sea level at 0.3-0.4 m/ka. The lowest point in the level of the Mediterranean (the so-called lowstand) probably occurred at 5.8-5.5 Ma.

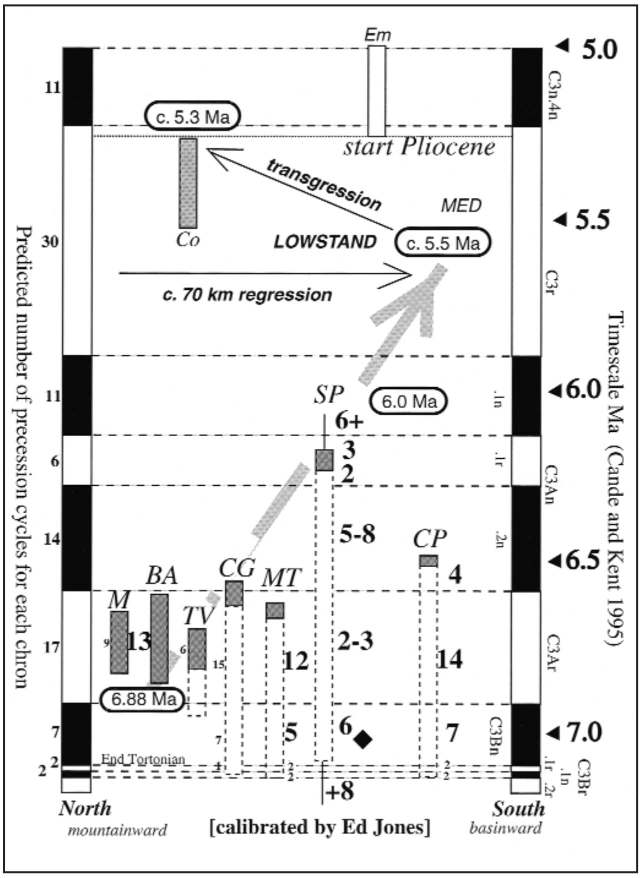


Figure 2. Results of the magneto-stratigraphic studies of Messinian sites on Sicily. This complex diagram shows a number of stratigraphic columns (M, BA, TV, CG, MT, SP and CP) with an upward transition from pre-evaporitic beds of the Tripoli Formation (unornamented), to basal evaporites of the Calcare di Base (shaded). The number next to each column is the number of observed depositional cycle in each chron at each site; these should always be equal or fewer in number than the predicted number. The resulting calibration charts the diachronous onset of evaporite precipitation across Sicily from which the rate of sea level fall (regression) may be established. Note that the marine transgression is much more rapid than the regression (Butler et al, 1999).

Transgression marked by accumulation of the 'second cycle' deposits, which all record reversed magnetisations (C3r), apparently occurred far more rapidly (200 ka), prior to the return to 'normal' marine conditions in the central Mediterranean (Trubi deposition) late in chron C3r.

So far a unified bio-astro-magneto-stratigraphy has proved impossible. Assuming depositional cyclicity in the first cycle and precursor sediments are eustatic in origin and forced by precession, they provide an absolute calibration of magneto-stratigraphy. Discrepancies with conventional biostratigraphy require diachronous colonisation and extinctions between sub-basins. Such diachroneity in biological 'events' should be expected during large magnitude sea level fluctuations and their associated local variations in water chemistry within isolated basins.

Debate over the Messinian event

The Sicily study then gives a new insight onto the salinity crisis. For most of the Messinian the level of the Mediterranean fell slowly, linked to the fall in world ocean level caused by a sharp glacial event. The seaways stayed open. If the Mediterranean itself dried up then this happened only for a short period in the late Messinian. However, much of the evidence for the nature of the Mediterranean basin floor during this time came from Sicily – clearly an area that never resided at these depths. Although the water returned across Sicily in the latest Messinian at a much higher rate than it fell, it still did so over a protracted period. There no evidence for a catastrophic flooding at the start of the Pliocene. Rather, this time represents a change in water chemistry accompanied by a sea level rise and recolonisation by a richly diverse fauna. The nature of the Mediterranean water body during the late Messinian is controversial Our existing studies suggest that it was not normal world ocean water but had a significant component of river input. It was however homogeneous across the Sicilian basins suggesting that these synclines had good communication with the broader sea.

This story of structure and sedimentation illustrates how a multidisciplinary approach to basin analysis can yield high-resolution results. It is now possible to quantify rates of geological processes with surprisingly high precision. However, to have much further faith in these models and results requires a broader view and the application of these methods to other sites around the Mediterranean. Fortunately there are many to target, and work is continuing apace.

Acknowledgements

The members of the Central Sicily Basins Project included Mario Grasso and Rosanna Maniscalco (University of Catania), Buffy McClelland and Bryan Finegan (Oxford University), Martin Pedley (Hull University) and Henry Lickorish, Ed Jones, Shona Keogh and the speaker (University of Leeds). Thanks to them all! The project was NERC funded.

Literature

Butler, R.W.H., Keogh, S.M. & Lickorish, W.H. 1998 (appeared 2000). Evolution of the Agrigento thrust-top basin, Sicily: Sedimentation and the tectonics of orogenic wedges. *Annales Tectonicae* **12**, 28-50.

Butler, R.W.H. & Lickorish, W.H. 1997. Using high resolution stratigraphy to date fold and thrust activity: examples from the Neogene of South-central Sicily. *J. Geol. Soc.* **154**, 633-643.

Butler, R.W.H., Lickorish, W.H., Grasso, M., Pedley, H.M. & Ramberti, L. 1995. Tectonics and sequence stratigraphy in Messinian basins, Sicily: constraints on the initiation and termination of the Mediterranean 'salinity crisis'. *Bull. Geol. Soc. America* **107**, 425-439.

Butler, R.W.H., McClelland, E. & Jones, R.E. 1999. Calibrating the duration and timing of the Messinian Salinity Crisis in the Mediterranean: linked tectono-climatic signals in thrust-top basins of Sicily. *J. Geol. Soc.* **156**, 827-835.

Keogh, S.M. & Butler, R.W.H. 1999. The Mediterranean water body in the late Messinian: interpreting the record from marginal basins on Sicily. *J. Geol. Soc.*, **156**, 837-846.

Lickorish, W.H., Grasso, M., Butler, R.W.H., Argnani, A. & Maniscalco, R. 1999. Structural styles and regional tectonic setting of the 'Gela Nappe' and frontal part of the Maghrebian thrust belt in Sicily. *Tectonics*, **18**, 655-668.

Speranza, F., Maniscalco, R., Mattei, M., Di Stefano, A., Butler, R.W.H. & Funiciello, R. 1999. Timing and magnitude of rotations in the frontal thrust systems of southern Sicily: a multidisciplinary approach. *Tectonics* **18**, 1178-1197.

LECTURE

Geology in war

Summary of lecture presented to the Society on Saturday 15th April 2000 by Prof Mike Rosenbaum, of Nottingham Trent University.

A review of military history reveals two major considerations that have influenced operations ever since large armies were first deployed. The first is the availability of communications allowing movement of troops and equipment. The second is the configuration and state of the ground, so controlling deployment of the opposing armies in battle. It must be remembered that armies cannot win in defence alone, and success requires first class leadership combined with the will to succeed and supported by adequate equipment and men.

Military geology involves the application of geological science to the decision-making processes that are required by military command. Consequently, the individual geologist needs to be professionally experienced in applied geology and also trained in military staff work and doctrine, in a strategy preferred to that adopted during the 19th century, when attempts were made to train army officers in geology.

The British Army was the first to use geologists in their professional capacity for military operations, during the First World War; geologists have provided advice to commanders in every major operation with which the British Armed Forces have since become involved. Following each major conflict, publications have drawn attention to the valuable contribution made by military geologists. However, financial pressures and the perceived lack of a need for more than a basic preparation for future armed conflict have resulted in few recommendations for increasing the establishment ever being adopted.

The importance of establishing an adequate and relevant database of information is now widely recognised. Geological mapping is able to provide an early indication of the type of ground to be expected during a military campaign, and the trend for its compilation has been towards digital recording in support of the existing paper information. The provision of geological information together with its interpretation and the means of giving advice are now established components of decision support within headquarters at Corps and Division levels. Generally the tasks have to be dealt with in emergency situations, and time is therefore very short by comparison with civilian projects. The primary requirement is a rapid assessment of the ground conditions within the context of the prevailing military situation. For the advice to be useful, it then has to be presented in a manner compatible with accepted military practice and avoid use of technical jargon.

Construction work is required in support of the battle: preparing defences, supporting an advance and consolidating new positions. Interaction of these works with the ground and the supply of natural materials, particularly water, requires characterisation and management sensitive to the contemporary military operations. Local water supplies, even if undamaged, are unlikely to be able to sustain the quantities required by the influx of large numbers of troops. Health risks from poor water, due not only to natural bacteria but also to deliberate contamination (from terrorist sabotage or nuclear, biological or chemical attack), require that suitable water supplies be established and developed early in a campaign.

The close link between the physical character of the battlefield and the underlying geology is fundamental, and gives advantage to the side that best appreciates the nature of the link during both the battle and the follow-through. This aspect is expressed not only in terms of troop mobility but also with respect to ground diggability and the maintenance of supply lines and defensive works. Late 20th century actions in the Falkland Islands, the Persian Gulf, Cyprus and mainland Europe explicitly demonstrate how military geology has been used, directly or indirectly, by the British armed forces in more recent years. The trend throughout the century has been of increased mobility during armed conflict, although the scale of operations has varied enormously.

Perhaps the most important geological lesson to have been learned in war has been that the military geologist must have basic data to interpret if he is to provide effective advice. Rapid evaluations, rather than financial strictures, are of the highest priority, and therefore the military geologist needs to be able to operate as an individual, as a consultant and as part of a team, and he must have the data accessible. This requires extensive training in peacetime, in order to establish access to the database and to exercise its retrieval in preparation for times of conflict.

A battlefield environment is not conducive to conventional scientific investigations, yet an accurate interpretation of ground conditions will be required within the generally very short timeframe of an operation. This demands the availability of a geologist who is trained in his science within the military command structure. He must also be a geologist of considerable versatility - for he must have a wide and deep knowledge of his discipline, and must be able to survive and operate under battlefield conditions, and he needs to understand military principles and procedures well enough to make his advice and decisions clearly and immediately relevant to the perceived military aim.

Literature

Rose, E.P.F. & Rosenbaum, M.S., 1993. British Military Geologists: the formative years to the end of the First World War. *Proceedings of the Geologists' Association*, **104**, 41-49.

Rose, E.P.F. & Rosenbaum, M.S., 1993. British Military Geologists: through the Second World War to the end of the Cold War. *Proceedings of the Geologists' Association*, **104**, 95-108.

Rosenbaum, M.S., 1997. Geological training for British Army Officers: A long-lost cause? *Journal of the Institution of Royal Engineers*, **111**, 182-183.

Rosenbaum, M.S., 1998. Background and recent applications of military geology in the British armed forces. In: Underwood, J.R., Jr., & Guth, P.L. (Eds.), Military Geology in War and Peace. *Geological Society of America Reviews in Engineering Geology*, **XIII**, 125-134.

Rosenbaum, M.S. & Rose, E.P.F., 2000. Operational roles for military geologists. In: Rose, E.P.F. & Nathanail, C.P. (Eds.), *Geology and Warfare*. Geological Society, London, in press.

EXCURSION

Minerals of the Northern Pennines

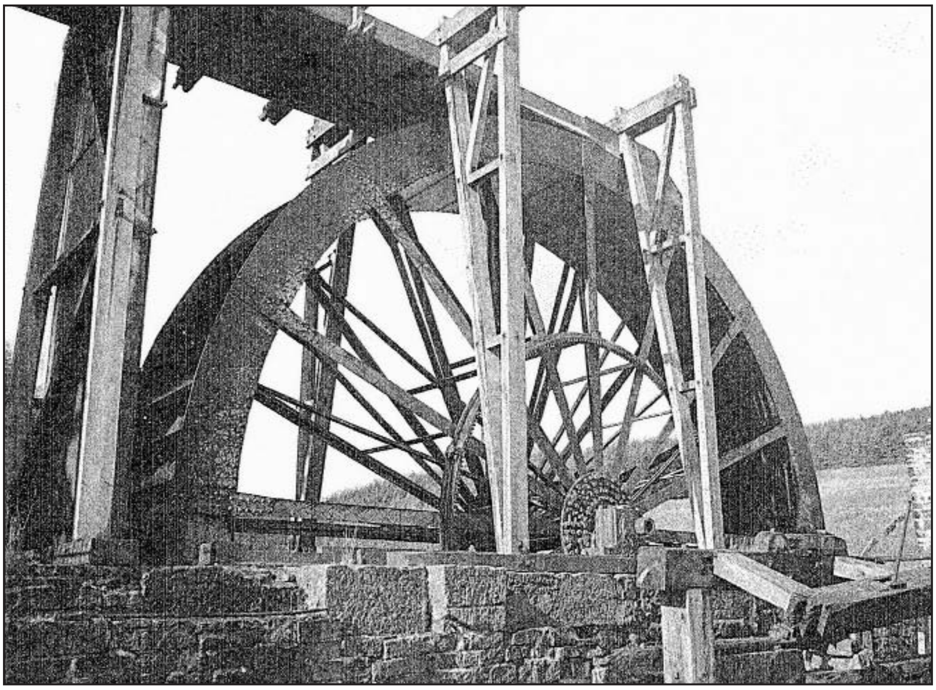
Leader: Trevor Bridges

Weekend 2nd-3rd October 1999

On a rather wet and blustery Saturday, 31 members of the Society met at 10.30 am in the car park at Cow Green Reservoir (810312) at the top of Teesdale; this was a record number for a weekend excursion. Our leader, Trevor Bridges, previously a member of the Society and still an active member of the Russel Society, had always been interested in mines and minerals. When he lived in Derby, the minerals of the Peak District were his passion, but his attention transferred to the Northerm Pennines orefield when he moved to live near Newcastle.

Cow Green Reservoir covers the site of Cow Green Mine, an important source of lead and iron ore, but subsequently for barytes until its closure in 1954. There is still plenty of evidence of past mining activity in the area. From the car park we walked a short distance to the north up the steep-sided rocky valley of Winter Hush. Joining this hush at an angle from the northeast was Green Hush. Trevor explained that hushing was a method used by miners to remove the waste rock from the area of a vein. They dammed a stream higher up the hillside, and periodically released the water in order to scour the outcrops of rocks and veins down the hill, giving them access for further quarrying of the ore. Mineralisation of this vein showed a brown impregnation of the country rock with iron and magnesium carbonates, including ankerite and siderite. There were traces of galena, but barite was more plentiful. Barite is confined to the outer zone of the Northern Pennines ore field, whereas the central zone is dominated by fluorite. The Lower Carboniferous country rock is unlike that in the Peak District, as it consists of cyclothem sequences of limestone, shale and sandstone with seat earth and an occasional coal seam.

Sir Kingsley Dunham, Director of the British Geological Survey 1966-1975, spent much of his professional life in the area, first as a student at Durham University and later as Professor of Geology, and became an authority on the orefield. Trevor related how Dunham's concepts of the mineralisation of the area had changed over the years. In 1934, at the end of three years of postgraduate research, he published a paper suggesting that a concealed granite intrusion might be responsible for supplying the mineralising fluids. Early in the 1950s, two research students from Cambridge approached him with a proposal for a gravity study of the Alston block. Their results showed a Bouger anomaly of reduced gravity across the centre of the area, indicating the possible existence of a granite pluton. In 1960, government funding was obtained to drill a borehole at Rookhope, and the granite was reached at more than



The Killhope water wheel at the Lead Mining Centre in Weardale.

300 m below the surface. However it had an eroded surface and was subsequently dated to the late Devonian; it could not be the provider of the mineralising fluids in the Carboniferous limestone. It has been suggested that the mineralisation may have occurred late in the Carboniferous, when relatively high geothermal heat flow up through the granite may have aided migration of mineralised fluids from the adjacent sedimentary basins.

We returned to the car park, where we examined an exposure of limestone displaying fossils of crinoids and corals, including Dibunophyllum, on a large, almost horizontal bedding plane, that had probably been used as a mineral dressing floor. We then walked south along the road to the Cowgreen Dam. On the way, we passed an exposure of "sugar" limestone, that is Melmerby Scar Limestone marmorised by heat from the Whin Sill. Its gritty texture has created a good growing medium for the alpine spring gentian in one of its few British habitats. Further along the road, outcrops of fine grained, dark crystalline dolerite were part of the Whin Sill, the massive sill that was intruded right across the northern Pennines and Northumberland in the late Carboniferous. Below the dam, the outflow cascades over the sill to form the spectacular waterfalls of Cauldron Snout, which looked very impressive between walls of eroded dolerite with columnar jointing. Looking back at the dam, Trevor pointed out that the eastern half of the dam is a concrete gravity structure where it stands on the strong and stable Whin Sill, while the western part is a rockfill embankment that imposes lower loads on the drift fill of a small buried valley.

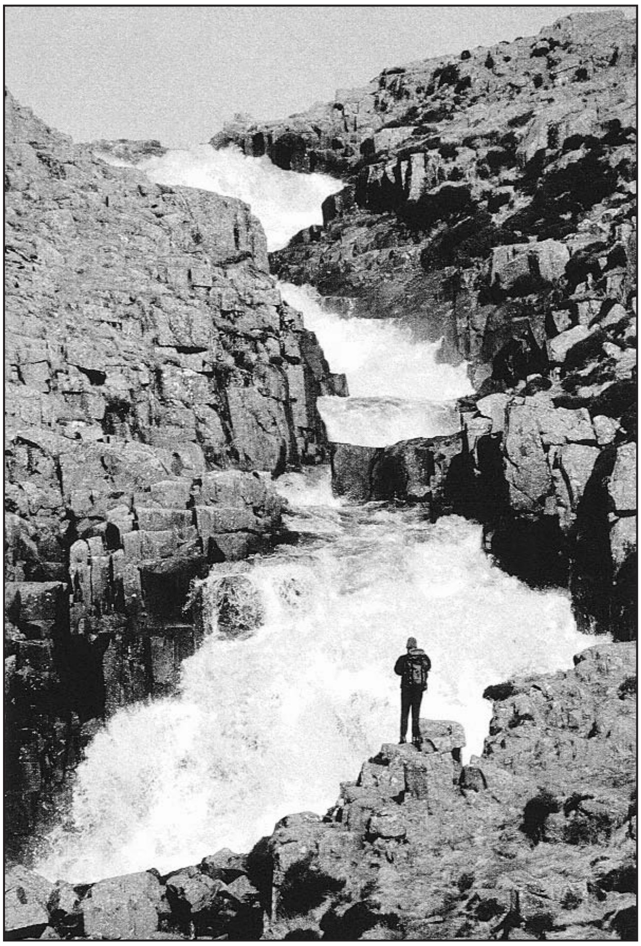
In deteriorating weather of the afternoon, we drove down Teesdale to Bow Lees Country Park (907284), on the landscaped site of a limestone quarry and crushing plant that closed in 1968. Here we grouped into fewer cars for a journey up a gated road onto the moors. We had permission from Raby Estates to visit the Pike Law workings (905314), but a ban on mineral collecting was one of their conditions for access. In pouring rain, we slithered down a steep rocky path into another hush, rather deeper and wider than the one at Cowgreen. Despite the weather, it was worth the effort, as the mineralisation was exceptional. We were in the fluorite zone, and there were beautiful purple cubes of the mineral, as well as large lumps of galena, ankerite, siderite and calcite. One specimen was found that demonstrated the change in mineralisation of a vein from ankerite on the outside to fluorite inside. A bonus find was an abandoned kestrel's nest, with a collection of small bird bones beneath it.

The Sunday was spent at Killhope Lead Mining Centre in Weardale (824433). We first walked across the road and up the hill to examine the sequences of sandstones, shales and limestones that make up the cyclothems, although there was no evidence of coal. About 100 m up the road, the bank was composed of a thick band of sandstone overlain by the Great Limestone, and the junction between the two beds formed the base of the Namurian, in marked contrast to the stratigraphy of the southern Pennines. There was some discussion about the wavy partings in the limestone. Were they best described as thin shales or as stylolites? Trevor related that the best ores have been found in the Great Limestone. Across the road, a stream section exposed thin mineral veins with ankerite, fluorite and galena in altered limestone; the mineralisation had hardened the country rock, so that the veins stood out as small waterfalls. There were also fossil beds with both Dibunophyllum and productids.

Back at the mining centre, we divided into groups for guided tours, firstly along one of the old adits into the mine. This has been modified with very realistic fibreglass in places, to create a circular tour that demonstrates the mining techniques. As the rain began to fall more heavily, we were joined by Trevor's wife Shelagh, who helped to show us around the outdoor exhibits. The large overshot water wheel, which is the symbol of the museum and was used to drive the machinery, has been renovated. The dressing floor has been restored so that visitors can see how the ore was concentrated by the women and children ready for dispatch to the smelters. Some members tried "hotching" - a process for separating out the heavier lead ore – and found it harder work than it looked. Finally we went inside to see examples of minerals and other museum acquisitions, followed by very welcome cups of tea. Trevor recommended a book recently published by the Friends of Killhope under the title *Out of the Pennines*; it contains 15 short papers by local enthusiasts about various aspects of the history of mining in the area (and has been very helpful in preparing this report).

Many thanks to Trevor and Shelagh for bringing the Northern Pennines orefield to life.

Judy Small



The waterfalls of Cauldron Snout, where the River Tees cascades over the Whin Sill.

EXCURSION

Ballidon Limestone Quarry

Leaders: Darren Middleton and Philip Loxley

Wednesday, 2nd June 1999

Sixteen Society members braved torrential rain and thunderstorms to visit Ballidon Quarry on the southern edge of the Peak District. The visit was led by the quarry managers who kindly provided excellent notes describing the quarrying operations. Transport around the site was in minibuses provided by the quarry operaters, Tilcon, part of the Anglo American Group.

Ballidon Quarry (at SK203556) lies just inside the southern boundary of the Peak District National Park, almost midway between Dove Dale and Matlock, and is visible from the High Peak trail. Quarrying started in the 1940s, rather later than most other quarries started in the area. The quarried product is mainly a limestone of very high purity, with about 99% $CaCO_3$. Around 60% of the output is used as a white filler powder in a variety of industries. Some of the coarser stone is used to make white concrete blocks in a plant on site, and some is used as roadstone chippings in a bitumen coating plant, also on site. Impure material is used for fill, including restoration work in the quarry.

The first excursion stop was a viewpoint overlooking the main quarry in the Bee Low Limestone, which was producing up to 6000 tonnes of stone per week. Site restoration could be seen on the northwest side of the quarry. Contoured screening bunds blanket the old quarry sides with a mix of loose fill and boulders to create an appearance similar to the natural slopes and gorges in the area. Subsequently some 20,000 trees of species appropriate to the area are planted, together with a seed mix to mimic the local flora. The key to the visual success of the operation lay in the placement and the size range of the stone blocks left protruding from the face of fill.

A zone of stone below the viewpoint had not been quarried and was described as a fault; its extension could be seen as a darker area in the opposite wall of the quarry. No bedding displacement could be seen across the fault, but the limestone is heavily brecciated, and the voids in it are filled with clays that make it uneconomic to quarry for high purity limestone. Discussion on the nature of the fault was cut short by the increasing intensity of rainfall and two very close lightning strikes.

The party retreated to the control room of the primary crushing plant. Broken stone from the blasted quarry faces is brought by dumper truck in 45 tonne loads to the primary crusher. It is then screened to remove material less than 40 mm in diameter, as this fraction contains almost all of the clay, iron oxides and other impurities. Product quality is also aided by the face loaders selecting only the larger and better material to fill the dumper trucks. Crushed material exceeding 40 mm is stockpiled for further processing.

Amelioration of the storm enabled the party to visit a face in the newer, northern part of the quarry, on a bench just below the original ground surface where the Monsal Dale Limestone was being removed, where it overlies the Bee Low Limestone. The Monsal Dale beds were deposited in a marine lagoonal basin in water about 30 m deep. The rock is darker in colour, with conspicuous fossils of corals, crinoids and productid brachiopods. It is very hard and commonly breaks with a conchoidal fracture, and is of lower commercial value than the Bee Low Limestone due to its higher content of impurities. Locally the limestone is heavily shattered, and slickensides were seen on fault planes. Exposed across the quarry face, two layers of pyroclastic material, separated by a thin limestone, were thought to be related to the Lower Matlock Lava. The volcanic sediment is finely laminated, suggesting its deposition in water; it is also very reddened, which is taken to indicate subaerial weathering after phases of uplift. It was thought that these volcanic horizons in the Monsal Dale Limestone had no other local exposures. The red clastic material made the rock only of use for low quality fill. Some of the limestone exposed on the same bench has been dolomitised; this is also unsuitable for the main quarry products.

The increasing downpour caused the party to retreat to shelter again, in the control room of the secondary crusher. In this plant, the clean limestone is further crushed, screened into particles of sizes down to 3 mm, and stored in hoppers ready for despatch.

The Ballidon Quarry had revealed to members some interesting contrasts between the Bee Low and Monsal Dale Limestones, and some insights to the geological problems of stone quarrying. In near cloudburst conditions, the quarry company leaders were briefly and informally thanked and the party departed wet but enlightened. The Society is grateful to the company, its managers and its staff, who provided our members with an excellent visit.

Alan Filmer

THE RECORD

The Society has welcomed 21 new members, and membership now numbers 387.

Field meetings

In May, Alan Dawn gave a preview of the Cool Peterborough exhibition that features the Deeping Elephant, followed by an afternoon visit to a quarry in the Oxford Clay.

In early June, there was a most interesting visit in pouring rain to Ballidon Quarry, near Ashbourne, led by the quarry management.

Later in June, John Aram and Albert Horton led an excursion to the Vale of Pickering and the nearby coast.

In July, Dave Bridge and Graham Worton led a trip to several sites in the West Midlands, that included a canal boat trip.

In September, Ian Thomas guided members round the National Stone Centre at Wirksworth.

There was an excellent weekend trip in October to study the geology and minerals of the North Pennines, including a visit to the Killhope mining museum. Trevor Bridges was the leader, and he gave the 34 members a fascinating weekend.

Indoor meetings

At the March meeting following the AGM we heard Dr Tony Waltham describe the geology and culture along the route from Nepal to Mt Kailas, the sacred mountain of western Tibet, illustrated by wonderful slides.

The April meeting heard Prof. Randy Parish describe evidence for the uplift of the Tibetan Plateau and the causes of the Indian monsoon, and also the contribution of the uplift of North America’s west coast mountains to the onset of the northern hemisphere glaciation.

The autumn meetings started in October, with Dr Duncan Friend talking about the enigmatic creatures of the Cambrian Burgess Shales in Canada, and describing how a palaeontologist unravels their secrets.

In November, about 100 members heard Prof Dianne Edwards describe “The Greening of Planet Earth”. Many Society members have a wide interest in the natural world, and this cross-discipline lecture was well received.

Our December lecture was by Dr Alf Whittaker who gave a suitably popular talk on the role of alchemy and mysticism in Mozart's Magic Flute, followed by the traditional cheese-and-wine.

In January 2000, well over 100 members heard Dr Rob Butler reveal the complex history of the drying up of the Mediterranean during the Messinian (late in the Tertiary).

In February, the departing President gave his much-trailed address, that fully justified his well-known personal affection for the Quaternary geology of East Anglia.

Events

The Society was represented at Wollaton Hall for two Rockwatch events and two museum events, with the EMGS stand staffed by Les Hall, Ben Bentley and Jack Brown. The display has also been to the Shakespeare Street Adult Education Centre and to the Stone Centre at Wirksworth.

Alan Filmer, Secretary

REVIEWS

Derbyshire Blue John, by Trevor Ford, 2000. Ashbourne Editions, Derbyshire. 112 pages A5, 70 colour photos, 29 figures, 1 873775 19 9, £5.95.

It is a rare privilege for a reviewer to be able to enthuse so completely over a book that is a complete success in so many ways. Trevor Ford's *Derbyshire Blue John* provides one of those privileges; it has all the key elements that every author and publisher yearns to achieve.

Blue John is the perfect subject. It is one of the very few British minerals that is important and famed on a worldwide scale. It can also claim to be unique to the Peak District. Fluorspar is common enough; blue (or purplish blue) fluorspar is also widespread; blue banded material is much less common; blue banded fluorspar that is of quality fit for ornamental carving is only worked at one other location (China); and large blocks of material for ornaments larger than trinkets have only ever been found in Treak Cliff. The mineral deposits of Castleton are truly unique.

To many, Trevor Ford is Mr Peak District (or more correctly Dr Peak District OBE). He has long been regarded (correctly) as the font of knowledge on anything geological in the Peak District; he has over 40 years of research experience in the area, notably on the mining and minerals and equally on the caves and karst. The second vital element for a good book is to have a knowledgeable author, and *Derbyshire Blue John* has the best possible.

The book covers every aspect of the mineral; there are excellent chapters on the geology, the mining and the cutting and preparing of ornaments and jewellery. One double page of colour photographs shows all the distinctive, named varieties of Blue John that come from the different parts of Treak Cliff's mineralised limestone. Not surprisingly, the book includes a chapter of fascinating detail on the mineralogy of Blue John, where there is still room for debate over the cause of the colouring. Trevor Ford ascribes the colour to lattice distortion, but retains doubts on the cause of this. He reviews the possible role of colloidal calcium, the less possible role of impurities, and the more likely potential for dislocation by uranium radiation, but he dismisses the old idea of colouring by hydrocarbons.

The history and use of Blue John occupies nearly half the pages in the book, as the author unfolds the story of the mineral starting from the discovery of its attributes around 1700, any notions of the Romans using Blue John having been debunked in a previous chapter. Early use in rather splendid fireplaces matured into the carving of the great vases that are now irreplaceable due to the declining availability of large blocks of the best-quality mineral. Today's modest jewellery production at Castleton is a mere shadow of the Blue John industry of 200 years ago, but it does continue a fine tradition.

The third element of a good book is down to the qualities of presentation and printing. Yet again, this book is an unqualified success. The text is so refreshing, because it is so comprehensible; it is clearly authoritative without being a heavy, and barely readable, learned treatise. It is well written, and is a captivating read - surely the aim of any good book (and one that many others could do well to emulate). For those who want more detail, there is a useful, selected bibliography that is properly referenced.

Derbyshire Blue John warrants high-quality colour printing, and it has it. The wealth of colour pictures are there to be treasured; they include images of so many of the most splendid and most famed Blue John pieces. Readers can judge for themselves as to which is the most magnificent - Shore's vase on page 86, Vallance's vase on p 87, or Woodruff's table on page 99; they are all 19th century pieces now in different museums, but they are all to be seen in the pages of this book.

A reader could expect to pay dearly for such a wealth of information and excellent presentation; yet the book retails at just £5.95. This is rare value (will other publishers please note what can be achieved). *Derbyshire Blue John* will sell like hot cakes in the Peak District and should also achieve worldwide sales among mineral enthusiasts. And it's not just for the specialist; anyone could enjoy reading it. This is a great book.

Tony Waltham

Holiday geology map: Peak District, by Neil Aitkenhead & Anthony Dennis, 1999. British Geological Survey, A3, 0 85272 340 7, £1.95.

One of the series covering holiday locations in Britain, this provides a new view of the Peak District. It gives a quick snapshot of the principal rock types and the nature of their formation, along with other geological features, such as the faulting and mineralisation. The language used is kept simple, to enable it to be understood by the typical Park visitor, and although it does refer to time periods it does not attempt to complicate things for the interested.

The main feature is a satellite view of the whole Peak District from 700 km in space overprinted with a simplified geological map. This works extremely well except that the locations and towns are printed in very small type (maybe necessarily for the compact map scale) which makes them a little difficult to read! There is also an oblique 3-D section through the Peak District showing the arch of the Pennine anticline, to help illustrate a textual explanation of the overall geological structure, but this is a little too small to be of great use. The format of the map makes it easy to carry around and the thick laminated paper should make it resistant to a fair amount of wear and tear. Altogether, this is an excellent publication, which should bring to the walker or holiday-maker in the Peak District, a basic understanding of the geology that underlies the beautiful landscape of the National Park.

Tony Morris

The Dudley limestone mines, by Steve Powell, 1999. Vol. 14, No. 1, Mining History (Bulletin Peak District Mines Historical Society), ISSN 1366 2511. 68 pages A4, 80 figures, £7.00.

Admittedly more West than East Midlands, the limestone mines of Dudley do provide a fascinating aspect of economic geology that is of more than parochial interest. Two Silurian limestone beds just 9 and 13 metres thick supported an amazing complex of mines, whose product was vital to the Black Country iron and steel industry. Quarrying evolved into underground mining around 1700, and a series of tunnels providing canal access direct to the mines became a success story that has made the hills of Dudley very special.

Sadly the 20th century at Dudley saw only the demise of the mines. Crown holes - those exciting surface collapses when bits of buildings and cricket pitches suddenly drop into oblivion - heralded the roof failures that were inevitable in the weak shales overlying the mined-out limestones. Just filling the surface holes was not enough; a fresh crown hole at Wrens Nest had to be filled in 1994 on the same site as a hole filled in 1962. The threat to roads, houses and people was such that entire mines have been filled in the last 30 years. The massive and expensive programme of ground remediation was a classic of its kind, and is described in this report.

Filling the mines was an undeniably terminal process, and this publication is therefore a valuable record of a lost heritage. It is a fascinating record of the miners' endeavour, the engineers' response to hazard, and the author's perseverance in gathering data. Some better maps to relate surface and underground features could have been welcome, but anyone drawn to the famous limestones of Wrens Nest Hill (to gain but a glimpse of the huge inclined pillars in the Seven Sisters mine gallery, now beyond massive railings) will find this volume both interesting and useful.

Tony Waltham

NOTES TO CONTRIBUTORS AND AUTHORS

Scientific papers. These are accepted on the understanding that they have not been published (or submitted) elsewhere. Shorter reports, news items, reviews and comments are all welcome, especially where they have a local interest.

Submissions. All material should be prepared and submitted in a format as close as possible to that of the *Mercian Geologist* since 1992. Please submit two copies of the full text and diagrams of scientific papers; only single copies are required of photographs and of the texts of shorter items. All texts should be machine-written on A4 paper, single-sided, double-spaced and with ample margins. The text should be followed by a complete list of the captions of all the diagrams, maps and photographs, numbered in a single sequence. It is helpful if text is also sent by e-mail, and is safer when cut and pasted into a message; please avoid attached files in the first instance. Electronic files should have plain text with no formatting. Illustrations and tables are required in hard copy only.

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Maps and diagrams. These are essential to almost any paper, and are of prime importance because they are conspicious and so tend to be studied more frequently than their parent text. Please take care over their preparation, and follow the guidance notes in the adjacent panel.

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References. Text references should be in the style of (Smith, 1992) or related to work by Smith (1992); use (Smith *et al.*, 1992) for more than two authors. All references are cited in an alphabetical list at the end of the text; please copy the style already used in *Mercian Geologist*, and cite journal titles in full.

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Correspondence and submissions. All items should be addressed to the editor, Dr Tony Waltham, Civ. Eng. Dept., Trent University, Nottingham NG1 4BU. The editor welcomes queries and discussion concerning any intended submissions; phone 0115 848 2133 or e-mail: <tony.waltham@ntu.ac.uk>.

PREPARATION OF MAPS AND DIAGRAMS

Size and shape. Each illustration should be of a shape that reduces sensibly to one or two columns width in the *Mercian Geologist* format and then has a size that reflects its importance and its amount of detail. Avoid large blank spaces within any diagram; place the key to create a good shape; north should preferably be at the top of maps — but this is not essential if rotation improves the shape.

Drawing. Figures drawn by hand should be about 140% of final print size. Draw them in black ink on good tracing paper. Pay attention to line weight; using Rotring pens, lines should be in the range 0.2 to 0.8. Each drawing must be enclosed in a frame drawn with heavy lines (0.5 thick); roads, contours and boundaries should normally reach to the frame.

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