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Doncaster Geodiversity Assessment

Volume 1 – Report

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Doncaster Geodiversity Assessment

Volume 1 – Report

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Foreword

Increasing pressure on land and the environment demands a greater awareness and understanding of the dynamics of our natural world in order to deliver a sustainable environment for the future. Biodiversity and the need for the Government to recognise, audit and plan for habitat and ecology is widely accepted and enshrined in UK legislation. However, the importance of the complementary concept of Geodiversity is only now gaining recognition, despite providing the foundations for habitats and species.

Geodiversity has a vital role in all aspects of the natural heritage and impacts on many sectors in economic development and historical and cultural heritage. For example, in the development of sustainable eco or geo-tourism (UNESCO Global Geoparks), Strategic Environmental Assessment, local authority structure and mineral plans, building stone resources, education and art.

Nationally important geological sites have been assessed and are protected by statutory measures, but other than Regionally Important Geological and Geomorphological Sites (RIGS) in some areas, there is little systematic inventory and evaluation of local sites or development of management measures for these sites. The introduction of Planning Policy Statement 9 (PPS9): *Biodiversity and Geological Conservation* has elevated the importance of geodiversity to a new level in England and Wales.

This report produced by the British Geological Survey seeks to address the aims of PPS9 and provides a foundation for developing a Doncaster Geodiversity Action Plan.

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Contents

Summary

This report describes a resurvey of Doncaster's RIGS (Regionally Important Geological and Geomorphological Sites) commissioned by Doncaster Metropolitan Borough Council (DMBC). It updates and expands the 1997 South Yorkshire RIGS Group survey of geologically important areas in Doncaster Barnsley and Rotherham.

Since 1997 the concept of geodiversity has moved up the planning agenda. The recent Planning Policy Statement 9: Biodiversity and Geological Conservation (PPS9), which places equal weight on biodiversity and geodiversity is a key driver in this process. The report will allow DMBC to develop a Doncaster Geodiversity Action Plan and incorporate this within the Local Development Framework.

RIGS resurvey work took place between January and March 2007. Site assessment data was collected using the UKRIG Site Assessment Form and entered into the UKRIGS GeoConservation database. Problems were encountered in using this database, especially importing and exporting data and the translation into a user-friendly report format. The database entries have been exported and appended to ESRI shape files for use in Geographic Information Systems (GIS).

Of the 28 sites listed in 1997, 23 are recommended for continued designation as RIGS, while five sites are proposed for removal from the list. Six new sites were surveyed and are recommended for designation as RIGS, bringing the total RIGS in Doncaster to 29. The new sites are:

- DR1-Denaby Woods –Mexborough Oxbow Lake
- DR2-Harlington Railway Cutting
- DR3-Cadeby Waste Water Works
- DR4-Nearcliff Wood Quarries
- DR5-Levitt Hagg Wood
- DR6-Barnburgh Cliff

1 Introduction

1.1 PROJECT BACKGROUND

Doncaster Metropolitan Borough Council (DMBC) is currently progressing the production of the Local Development Framework (LDF), the new style development plan. An important aspect of the LDF system is the requirement for policy formulation to be underpinned by a robust and credible evidence base.

Geodiversity can be defined as, “the variety of rocks, fossils, minerals, landforms and soils, along with the natural processes that shape the landscape” (Stace and Larwood, 2006). Development can harm it both directly (e.g. mineral extraction, road building) and indirectly (e.g. air pollution), but may also offer opportunities to create more rock exposures, or planning permission may insist on mitigation, such as future monitoring and maintenance work.

In 1997 Doncaster, with Barnsley and Rotherham, undertook a survey to identify the geologically important areas of the Borough (see Figure 1 for authority boundaries). However, since the 1997 survey the concept of geodiversity has moved up the planning agenda as authorities start to move beyond surveys and develop Geodiversity Action Plans. A key driver for this is Planning Policy Statement 9: Biodiversity and Geological Conservation (PPS9), which places equal (and considerable) weight on biodiversity and geodiversity (see section 1.3).

BGS was contracted to undertake a desk and field resurvey of these existing Regionally Important Geological/Geomorphological Sites (RIGS), suggest up to five further sites for designation as RIGS and to report the results of this work.

1.2 PROJECT OBJECTIVES

The objectives of this project are to:

- Compile a desk summary of the geology of Doncaster, a stratigraphic column highlighting the strata that can be seen within Doncaster, and accompanying summary maps in A3 format.
- Present the above to a workshop in February 2007 to seek views on the content of the background document and whether any sites of importance were omitted from the 1997 survey.
- Re-survey the 27 existing RIGS within Doncaster, plus any additional sites identified as a result of the workshop, using the UKRIGS Field Record and Site Assessment form
- Present the results of the survey work as a final report and database linked to GIS layers in ESRI shapefile format.

1.3 LEGISLATIVE AND POLICY CONTEXT

The introduction of PPS9 by the Office of the Deputy Prime Minister (ODPM, now DCLG, Department for Communities and Local Government) has elevated the importance of geodiversity to a new level in England and Wales. In PPS9, the Government’s objectives for planning include:

- **to promote sustainable development** by ensuring that biological and geological diversity are conserved and enhanced as an integral part of social, environmental and economic development, so that policies and decisions about the development and use of land integrate biodiversity and geological diversity with other considerations.

- **to conserve, enhance and restore the diversity of England's wildlife and geology** by sustaining, and where possible improving, the quality and extent of natural habitat and geological and geomorphological sites; the natural physical processes on which they depend; and the populations of naturally occurring species which they support.

The first of six key principles in the document states:

- Development plan policies and planning decisions should be based upon up-to-date information about the environmental characteristics of their areas. These characteristics should include the relevant biodiversity and geological resources of the area. In reviewing environmental characteristics local authorities should assess the potential to sustain and enhance those resources.

2 Geodiversity and its importance

International recognition of the need to conserve biological diversity led to the UN Convention on Biodiversity agreed at the Rio Earth Summit in 1992 and the subsequent signing by over 160 countries. Since the UK government published 'Meeting the Rio Challenge' in 1995, most local authorities or regions in the UK have prepared and implemented Biodiversity Action Plans (BAPs) for their areas, and biodiversity is now accepted as an essential element in sustainable development planning and management strategies.

Until relatively recently the parallel concept of geodiversity had attracted little interest, despite its fundamental importance in underpinning biodiversity by providing the substrates.

Geological and landscape features, other than those already afforded some measure of protection such as SSSIs, are often seen as sufficiently robust not to require active management or action planning. All geological features are potentially vulnerable. In addition to threats posed by inappropriate site development and the infilling of quarries, the encroachment of vegetation, natural weathering and general deterioration with time may threaten to damage or obliterate important geological features. This situation would not be tolerated in wildlife or archaeological sites of comparable scientific or educational value.

The geodiversity of an area may be considered as one of its chief natural resources. A key starting point is an appreciation of the most up to date available understanding of the area's geology, landforms and soils, together with the processes and phenomena which have formed them and continue to influence them. An area's geodiversity thus encompasses:

- sites or natural features which are deemed worthy of some form of designation or protection for the quality of Earth heritage features displayed
- sites or natural features where representative examples of the area's Earth heritage may be seen
- sites and natural features currently employed in interpreting Earth science
- resource potential for geotourism and education
- the whereabouts and nature of past and present working of mineral products
- the influence of earth science in shaping the man-made environment, urban landscapes and architectural heritage
- natural hazard management
- the inter-relationship and inter-dependence between Earth heritage and other interests, for example biodiversity, arcaheology, history
-

Documentation of an areas' geodiversity may include:

- sites with geological exposures
- materials collections and sites and other records such as borehole logs
- published literature and maps
- the historical legacy of research within the area

2.1 GEODIVERSITY – WHY IS IT IMPORTANT?

Geodiversity is fundamental to almost every aspect of life – all raw materials that cannot be grown and all energy that cannot be generated by renewables have to be found using geological science.

A clear understanding of geology is also vital to the design and location of buildings, roads, railways and airports as well as to the safe control of waste disposal, and the management of a wide range of natural and man-made natural hazards. All are aspects of geodiversity.

An awareness of geodiversity helps us to understand our environment and predict environmental change in the future. Geological research demonstrates that surface environments are continually evolving through natural self-regulating systems involving the Earth's crust and mantle, oceans, atmospheric processes and life forms. Human activity imposes further pressures and changes to these natural cycles, which pose great challenges to modern society. Exhaustion of finite resources such as fossil fuel and global climate change are two of the most pressing. Only by studying the geological record can we hope to predict the earth's response to these changing conditions.

The recognition of natural and cultural heritage features and their sustainable management are today accepted as important functions within a civilised society. The importance of the range and diversity of Earth heritage features – the 'geodiversity' - of any area is as important a facet of its natural heritage as its wildlife interests. Conservation, sustainable management, educational use and interpretation of geodiversity are thus as important as that of biodiversity or archaeology.

However, geodiversity is not, or should not be regarded merely as concerned with conservation of Earth heritage sites or features – it has a vital place in all aspects of natural heritage and impacts in fields as varied as economic development (for example, supporting the development of geotourism in the new UNESCO European Geopark Network), building stone resource development, education and lifelong learning, archaeology, art and wildlife. Geodiversity may be one of the most significant areas of heritage interest in areas of high landscape value, or areas previously or currently affected by significant mineral extraction.

Geodiversity interests need to be integrated into other policies and processess relating to sustainable development including:

- Strategic Environmental Assessment
- Local Development Framework and mineral plans
- The Water Framework Directive
- EU Soil Protection Directive
- Local Biodiversity Action Plans

An appreciation of geodiversity is important for a comprehensive understanding of many aspects of biodiversity. It also offers substantial opportunities to enhance the conservation, management, educational use and interpretation of such related features. Because it has hitherto received little serious consideration, geodiversity needs to be addressed and evaluated by expert earth scientists.

3 The Geology of Doncaster

3.1 INTRODUCTION – BEDROCK

The oldest rocks that are found at the surface in Doncaster belong to the Pennine Middle Coal Measures Group of the Carboniferous System (Figures 2 – 4) and whilst older rocks have been proven by colliery shafts and boreholes and were once highly significant to the coal mining industry, these are underground and not considered relevant to this report.

The configuration of landmasses across the earth during Carboniferous times was very different from today. By the beginning of the Carboniferous Period, roughly 360 million years ago (Ma), the area destined to become South Yorkshire was part of a continent known as Laurasia that had moved to a position almost astride the equator. At this time much of what is today northern England began to be progressively submerged beneath a wide, shallow tropical sea, in the clear, warm waters in which beds of limestone accumulated. Periodic influxes of sand and mud, deposited by deltas building from a landmass to the north or north east, periodically established swamp or delta top environments, occasionally with the development of lush tropical forests. The evidence for these conditions is preserved today as the layers of sandstone and mudstone of the Carboniferous rocks. As Carboniferous times progressed, tropical forest cover became much more frequent, the remains of which are preserved today as the coal seams of the Coal Measures.

Towards the end of Carboniferous times, about 290 million years ago, that part of the earth's crust on which the Carboniferous sediments had been deposited continued to drift northwards. Major Variscan earth movements associated with the formation of the supercontinent, Pangaea, once more created mountains across what became northern England. By about 280 million years ago, during the early Permian Period, northern Europe was one of the world's great deserts and the area that is today the Pennines probably consisted of mountains, with valleys choked with rock debris broken from these rapidly eroding barren uplands. Up to 500 m of Carboniferous rocks were eroded by this desert erosion, forming huge wind-blown sand dunes that covered much of a comparatively low gently rolling plain that sloped gently eastwards into the subsiding North Sea Basin. These are the 'Yellow Sands Formation' that is very occasionally seen at the base of the limestone escarpment in the western part of Doncaster today.

This Permian desert was soon inundated by the rapidly advancing waters of a sea, known to geologists as the Zechstein Sea. This occupied an area within a subsiding basin, flanked by uplands to the south and west, which included that of the modern North Sea and stretched into Eastern Europe. Sediments deposited in the Zechstein Sea record five major and numerous minor cycles of sea level change, with periods of high salinity, in part due to periods of evaporation of substantial parts of the sea, resulting in the deposition of repeated sequences of carbonate, evaporite and clastic sediments.

The earliest Zechstein sediments in Doncaster, associated with the first phase of inundation by the sea, comprise a muddy dolostone (formerly termed limestone) sequence (formerly called the Lower Permian Marl, but now included as the lower part of the Cadeby Formation), which was deposited at the south-western edge of the North Sea Basin in a large river estuary or a lagoon. With the sea level continuing to rise, a succession of dolostones was deposited, which, from the common occurrence of the magnesium carbonate mineral dolomite, was previous known as the Lower Magnesian Limestone (now Cadeby formation). A well-known feature of the Cadeby Formation is the presence of very well preserved fossilized reefs composed of bryozoans, algae, bivalves and brachiopods. These were formed in shallow water, very near to an ancient shoreline to the west.

With the next major change in sea level and the regression of the Zechstein Sea into the centre of the marine basin to the north-west, the land reverted to a low lying, wide coastal plain containing transient lagoons and playa lakes into which sediments derived from an arid hinterland to the west and south were deposited. This Edlington Formation (formerly The Middle Permian Marl) comprises calcareous mudstones, with occasional layers of gypsum that indicates the periodic incursion and evaporation of an increasingly saline Zechstein Sea.

Another substantial rise in sea level during the middle of the Permian Period saw the land once again inundated, with a return to shallow shelf conditions and the deposition of the dolomitic limestones of the Brotherton Formation (formerly the Upper Magnesian Limestone) near to the ancient sea shore.

Once again, the Zechstein sea level dropped with a return to a palaeoenvironment dominated by lagoons and playa lakes, where layers of anhydrite and rock salt were formed; especially to the north and east of the region and extending into north-east England, where thick deposits were laid down in the centre of the still subsiding basin. At the end of the Permian, 250 million years ago, when this Roxby Formation was formed, the Zechstein Sea finally dried up and the region remained arid and was covered in thick spreads of sandy fluvial deposits, commonly with pebbles and laid down as flash floods, that were derived from the erosion of upland areas to the south. Although in England there are no obvious boundaries visible in the rocks, the deposition of the Sherwood Sandstone Group (formerly Bunter and Lower Mottled Sandstones) marks the transition from the Permian to the Triassic Period, which ended 205 million years ago.

Successively younger rocks to the east of the region record geological events up to modern times, in Doncaster these are absent and there is no tangible evidence of the geological history until the deposits left by ice sheets during the glacial period of the Quaternary which began here about two million years ago. However, based on the geological record found in the surrounding regions, some general assumptions can be made. The latest Triassic saw the continuation of desert conditions, dominated by dust storms.

For much of the Jurassic Period the district was covered by shallow open seas, with mudstone and at times limestone deposition, but it is possible that in the middle part of the period, northern and western areas experienced brackish and freshwater depositional conditions, with transient emergence and erosion. Similar mainly nonmarine and periodically emergent conditions probably continued during much of the early Cretaceous. In the late Cretaceous, however, the sea in which the Chalk was deposited covered the entire district. During the Tertiary, differential uplift and the imposition of an overall easterly dip resulted in prolonged erosion, which removed all the post-Triassic rocks from the district and exposed Permian rocks in the extreme west. The westerly and northerly flowing drainage pattern evolved during this time.

3.2 INTRODUCTION – QUATERNARY

At the start of the Quaternary, which commenced approximately 2.5 Ma and is commonly referred to as the ‘Ice Age’, an episode of global cooling caused polar ice sheets to extend southwards to cover much of Great Britain and Northern Europe. During the Quaternary the climate oscillated between colder (glacial) and warmer (interglacial) stages. Study of sediments, landforms and fauna onshore and offshore have identified 14 to 17 stages of alternating cold glacial and warm interglacial conditions in Great Britain. The extensive ice sheets, which in places were over 1 km thick, resulted in erosion and modification of the existing landscape. The effects of persistent freeze-thaw action in ground, which was often very deeply frozen, and the deposition of a variety of glacial sediments further modified this pre-existing landscape.

The most recent glaciation, the Devensian, ended around 11,500 years ago, marking the beginning of the Holocene or recent period and deposits reflect erosion and deposition in a varied succession of environments during much milder climatic conditions. Fluvial deposits occur in almost all valleys or river courses and are still forming. These include a wide range of deposits including clays, silts, sands and gravels. Landslides occur in many areas and are not necessarily limited to steep slopes or hillsides. Peat deposits also developed during the Holocene after the glaciers retreated and occur both in local topographic lows in the deglaciated landscape and as extensive expanses of blanket bog over areas of high ground.

In Doncaster, Quaternary deposits cover 60 per cent of the land (Figures 5 and 6), generally being most extensive and thickest in the low-lying areas. Much of the form of the present day physical landscape derives from the effects of this prolonged period of ice cover and its subsequent melting. This has strongly influenced settlement patterns agriculture and, in historical times, man has diverted some of the rivers during high tides to produce extensive spreads of artificially induced alluvium, or warp to raise and fertilise the land.

The interpretation of the Quaternary deposits provides a wealth of information on the environments of the recent geological past. Information from glacial landforms and the nature and morphology of glacial deposits is essential to the understanding of these climatic conditions and may provide valuable insights into likely future environmental changes related to global warming. The study of Holocene fluvial sediments allows interpretation of the evolution of rivers or streams, including extreme events such as flooding.

BGS has subdivided Britain into a number of Quaternary domains, based on the occurrence of distinctive Quaternary landform-sediment associations and structural characteristics. Doncaster is covered by three Quaternary domains (Figure 7):

1. Plateau and Valley Domain
2. Dissected Till Domain
3. Lowland Basin Domain

Within the district there are deposits attributable to the last three British Quaternary stages (the Ipswichian, Devensian and Flandrian), and also to an older, pre-Ipswichian, glacial stage. Consequently, the long, early part of the Quaternary appears to represent a continuation of the denudational regime that had persisted during Tertiary times. The oldest deposits, of pre-Ipswichian glacial origin, indicate the existence of a thick cover of ice derived from the north and north-west, beneath which deep subglacial incision and deposition took place; fluvioglacial meltwater deposits entered the district from the south and west during deglaciation. Subsequent fluvial incision occurred just prior to the temperate Ipswichian Stage as a result of the sea level being at or more than 13 m below OD, which suggests retarded glacioeustatic effects. As sea level rose to about, or just above, OD during this interglacial, estuarine deposits formed in the incised drainage courses.

Somewhat later, the rivers Don and Idle deposited extensive spreads of river terrace deposits (Older River Gravel on some maps). In the cold Devensian Stage, which apparently began about 120 000 years ago, sea level fell to more than 20 m below OD, again reflecting glacioeustatic effects, and rivers crossing the district incised wide valleys directed towards the Humber Gap to the east. Periglacial conditions, indicated mainly by cryoturbation structures and ventifacts, prevailed during at least part of this long incision phase. However, except possibly for some fluvial sand and gravel now deeply concealed beneath the Hemingbrough Formation, and also possibly some head, there is no evidence of deposition until late in the Devensian.

Then, probably about 18 000 years ago, glacial blockage of the Humber Gap impounded a large lake (Lake Humber) across much of the district and adjacent areas. The lake rose initially to about 30 m above OD, sand and gravel being deposited around its margins. During this high-level lacustrine phase a tongue of ice surged southwards down the Vale of York and into northern and eastern parts of the district, depositing sand and gravel into the lake. The ice soon melted and the lake level fell, apparently transiently to as low as 4 m below OD, before establishing a longer lasting level at about 9 m above OD. Lake Humber finally disappeared, apparently by filling up with sediments, which are known as the Hemingbrough Formation.

Rivers then deposited sandy levees as they initiated courses across the emergent lacustrine plain. In the last millennium of the Devensian (which by definition terminated 10 000 radiocarbon years ago), blown sand accumulated in places, and some ventifacts and cryoturbation structures at the top of the Devensian glacial and lacustrine deposits may have formed at this time.

At the beginning of the Flandrian or slightly earlier, breaching of the glacial deposits in the Humber Gap allowed the rivers crossing the district to incise their courses down almost to 20 m below OD, again in response to the continuing eustatically low sea level. As the sea rose to its present level later in the Flandrian, alluvium eventually filled these incised courses and spread thinly but widely beyond them, locally covering peat that had developed in the prevailing wetter climate and more waterlogged conditions.

3.3 GEOLOGY AND LANDSCAPE – NATURAL AREAS

There is a fundamental relationship between the bedrock geology and the topography and landscape of the Doncaster area. Natural England has subdivided England into areas each with a unique identity resulting from the interaction of wildlife, landforms, geology, land use and human impact. Doncaster is covered by three Natural Areas (Figure 8) which closely match the bedrock geology (Figure 3):

1. Coal Measures
2. Southern Magnesian Limestone
3. Humberhead Levels

The Coal Measures Natural Area, in the west of the borough, coincides with distinctive scarp and dip slope topography resulting from the folding of the Carboniferous rocks, the differential erosion of the sandstones and intervening shales and the drainage patterns of the rivers Don and Dearne.

The Southern Magnesian Limestone Natural Area coincides with the Permian rocks that occupy the west-central part of the region. It is generally characterised by well drained rolling countryside, with minor landforms controlled by local faulting and folding, and a western boundary sharply defined by the very distinctive limestone escarpment.

The Humberhead Levels Natural Area concides with the Triassic rocks and unconsolidated Quaternary sediments that are found in the central and eastern part of the region. East of a line that runs approximately from Arksey, Doncaster to Tickhill, the Sherwood Sandstone that comprises the Doncaster and Rossington Ridges passes into the relatively flat, lowland areas of eastern Doncaster, where the solid bedrock is covered by sand and gravel, silt, clay and peat.

These Natural Areas are also readily distinguishable on the NEXTMap Britain Digital Surface Model (Figure 9).

3.4 CARBONIFEROUS

The bulk of the Carboniferous rocks in Doncaster lie deeply buried beneath a thick sequence of younger rocks to the east of the limestone escarpment, which essentially defines its western geographical boundary. Historically, their position was marked by numerous pit heads and collieries that, until recently, contributed greatly to the economic wealth and growth of settlements in the borough. Details of the geology, as seen in numerous colliery shafts and boreholes, are available in BGS Memoir 88; The Geology of the country around Goole, Doncaster and the Isle of Axholme and other mine records but other than to note that landscaped coal waste tips now add to the natural topography of the area, these are considered beyond the scope of this report.

The upper part of the Pennine Coal Measures Group of Carboniferous age exposed at the surface in Doncaster form an insignificant part of the geology of the borough and occur west of the limestone escarpment around Denaby, Mexborough, Barnburgh and the areas west of Hickleton, Hooton Pagnell and Clifton.

The Coal Measures rocks comprise a succession of largely mudstones and siltstones with subsidiary sandstones, seatearths (fireclays) and coals, which occur in a cyclical sequence throughout and reflect changes in sea level and repeated transitions between a marine and freshwater environment. Sedimentological characteristics of the Coal Measures indicate mainly lacustrine, fluvial and swamp deposition on an extensive and flat coastal plain, with sediments being derived from the ancient and long eroded Caledonian mountains to the north.

Medium grained sandstones form the most distinctive topographic features and in places stand out as bold escarpments but, in the district, these vary considerably in thickness and quickly die away laterally. The mudstones and siltstones occupy the intervening, lower lying areas.

Although the exposed carboniferous rocks in Doncaster are of limited geographical extent, they coincide with important structural and topographic features in the region. The Don Monocline and the North and South Don faults have controlled the river courses of the Dearne and the Don and have strongly influenced the distribution of younger strata and the development of distinctive landforms that can be seen around Mexborough, Conisbrough, along the Don Gorge to Doncaster and at Cusworth Hall. Significant Carboniferous formations are as follows (representative geodiversity sites are listed in square brackets):

3.4.1 Pennine Middle Coal Measures Formation

3.4.1.1 Mexborough Rock [D6-Denaby Lane; D166-doncaster Road]

A medium grained sandstone that forms a north-west trending ridge from Mexborough to Adwick-upon-Dearne and a north-east trending escarpment at Denaby Wood, plus a small but very distinctive feature to the immediate west of Old Denaby. Together, these provide good evidence of the position and influence of the Don Monocline. Mexborough Rock has been locally exploited as a building stone and contributes to the character of the local historic built environment and has been a good source of water supply.

3.4.1.2 Shafton Coal

With a maximum thickness of 1.5 m, this was once the highest of the important productive coal seams. Whilst once important underground, it was also once mined extensively at outcrop and in shallow workings at Denaby Wood (Figure 4).

3.4.2 Pennine Upper Coal Measures Formation

3.4.2.1 Ackworth Rock [DR2-Harlington Railway Cutting]

A medium grained buff coloured sandstone that forms a topographic feature to the west of Barnburgh but rapidly thins out at Harlington and appears again south of the Don at Denaby Wood (Figure 4).

3.4.2.2 Dalton Rock [DR3-Cadeby Waste Water Works; DR6-Barnburgh Cliff]

A medium grained buff coloured sandstone that appears between High Melton and Cadeby and also forms small topographic features in the area to the west of the limestone ridge to Hickleton.

3.4.2.3 Wickersley Rock

A medium grained buff coloured sandstone that forms a prominent feature at Stotfold and at the edge of the borough at Howell Wood, north-west of Clayton.

3.4.2.4 Ravenfield Rock

A medium grained buff coloured sandstone that forms small features to the south-west and north-west of Hooton Pagnell.

The highest Coal Measures in the area are mudstones and subordinate sandstones with thin coals, the topmost beds of which are usually stained red, the result of weathering of the Upper Carboniferous strata during the period of uplift and erosion in an arid climate that was a feature of the Permian period. Exposures are very rare and are usually only evident from boreholes, colliery shafts, clay and brick pits, cuttings, trenches and miscellaneous excavations.

3.5 PERMIAN

3.5.1 Yellow Sands Formation (formerly Basal Permian Sands) [D4- Watchley Crags; D15-Melton Park]

In much of South Yorkshire the denuded and weathered top of the Carboniferous sequence is covered unconformably by a friable and locally incohesive sandstone which varies from 0 – 30 m in thickness. Evidence from boreholes within the district indicates that the Yellow Sands Formation form a nearly continuous spread, but some boreholes failed to prove the deposit and it is uncertain whether the thickness variations mainly reflect irregularities in the surface on which the sandstone was deposited or an undulating top to the sandstone. The isolation of some of the thicker sequences suggests that deposition may have been in localised dune fields.

In boreholes, the sandstone is predominantly pale to medium grey and, more commonly in its upper part, bluish grey. It is mainly fine to medium grained, fairly well sorted and dominantly composed of quartz. The constituent sand grains are rounded or sub-angular and their surface is frosted in a manner suggestive of wind-abrasion and implies an aeolian origin. However, current bedding appears to be due to water action, so that it seems likely that the products of wind erosion were finally deposited under water, further evidenced by the occasional presence of argillaceous layers.

At outcrop, the Yellow Sands Formation is found only occasionally in the west of Doncaster, immediately beneath the limestone that forms the escarpment that essentially defines the western boundary of the borough. Where the sandstone is weathered the ferruginous component of it weathers from the bluish grey seen in boreholes to a yellow or orange-yellow colour.

Near Hampole, between Hooton Pagnell and Hickleton, at High Melton and at Conisbrough there are exposures of yellow, current-bedded sand that were formerly worked as building and moulding sand but, in no exposure are these beds more than 20 ft. thick. Elsewhere, the Yellow Sands Formation is not exposed.

3.5.2 Cadeby Formation (formerly Lower Magnesian Limestone) [DR4-Nearcliff Wood Quarries; D300-Conisbrough Caves East; D302-Conisbrough Caves South]

The Cadeby Formation comprises a white to grey, calcitic and dolomitic carbonate sequence, generally up to 80 m, and locally more than 100 m thick. It forms the main topographical feature, a major escarpment, along the west of the Permian outcrop that extends the length of its 300 km outcrop. Locally there is also a fault bounded outlier at Conisbrough and the escarpment is transected by the Don Gorge.

It comprises a thick sequence of limestones laid down in a shallow shelf marine environment at the edge of the Zechstein Sea and generally thickens to the east. During its formation, the calcium carbonate sediments of the Cadeby Formation were dolomitised, the result of chemical reaction with the increasingly hypersaline sea.

The lower calcareous mudstone (marl) facies of the Cadeby Formation (formerly Lower Permian Marl) appears to be absent from Permian strata that outcrop in the west of the borough and is known only from its occurrence in boreholes, in thicknesses of up to 4 m. It consists of pale or, more rarely, dark grey, flaggy to massive, calcareous and/or dolomitic mudstone and siltstone, with thin beds and lenses of argillaceous dolomitic limestone in places. It contains a restricted fossil assemblage consisting mainly of carbonaceous plant debris, fish debris, foraminifera and a locally abundant calcareous macrofauna, notably of bryozoans and brachiopods.

The Lower Marl Facies was deposited in shallow coastal lagoons, which passed laterally into a shallow marine shelf, on which were deposited the limestones of the Cadeby Formation.

The Cadeby Formation may be divided into two major stratigraphical subdivisions, the lower being the Wetherby Member and the upper the Sprotbrough Member separated by the Hampole Beds. These in turn are divided into several rock-types.

3.5.2.1 WETHERBY MEMBER [DR6-BARNBURGH CLIFF; D11-HAZEL LANE QUARRY; D4-WATCHLEY CRAGS; D15-MELTON PARK; D133- HOOTON PAGNELL; D13-NORTH CLIFF QUARRY; D5- HOOTON PAGNELL VILLAGE POUND; D20–22-CADEBY CLIFF - CONSTITUTION HILL; D112-PARKNOOK QUARRY; D28-POT RIDINGS WOOD RAILWAY CUTTING]

The Wetherby Member consists mainly of well-bedded fine grained to coarsely granular limestone and ooid-limestone, appreciably dolomitised and generally forming thick parallel beds, although small-scale cross-bedding and ripple-bedding are present locally. In places the beds are fossiliferous, but the fauna is rich in individuals rather than in species. Associated with these beds are masses of unbedded limestones, commonly referred to as reef-limestone, which are frequently crowded with fossils. Brachiopods occur in the reefs, though they are rarely found in the bedded limestones.

At the base a few feet of sandy limestone have been observed in places. Above this, ooidal limestones are the most important constituent, forming thick beds that are frequently fossiliferous. The ooids are small, well-formed and comparatively little altered. Many of the beds clearly show that they originally contained normal ooidal grains plus shell fragments and that both these constituents became completely crystalline during dolomitisation. With the ooid-limestones are pisoid-limestones (pisolites), a rock-type that is more common in the southern portion of the area. Some beds contain rhombs of dolomite that are clearly visible.

Near the base there are lenticular or irregular masses of hard, fine-grained, unbedded reef-limestone, which is white or cream in colour and locally brecciated. They consist largely of unbroken shells and fragments of lamellibranchs, brachiopods and bryozoa, accompanied in places by gastropods and foraminifera. Later alteration appears in some cases to have resulted in the obliteration of the fossils and the production of hard, compact, fine-grained limestone.

3.5.2.2 SPROTBROUGH MEMBER [D28-POT RIDINGS WOOD RAILWAY CUTTING; DR5 LEVITT HAGG WOOD; D94- WARMSWORTH QUARRY; D78- WARMSWORTH PARK]

The Sprotbrough Member consists mainly of finely or, less commonly, coarsely crystalline dolostone, some of it minutely cellular due to the recrystallisation of ooids; locally there is also some less altered ooid-limestone. The subdivision is practically unfossiliferous.

It commonly exhibits large-scale cross-bedding and wedge bedding that is one of the most striking features of the Sprotbrough Formation. Individual beds thicken and thin rapidly; thus in a few metres beds may thicken to as much as one metre and just as rapidly thin out.

Two main types of dolostone are found. The more abundant is a grey, white, cream or buff, crystalline, often saccharoidal dolostone that is largely composed of dolomite rhombs. Differences in cementation account for the variation in hardness between hard, compact, crystalline varieties and others, which are so friable as to break down readily to 'dolostone sand.' Stylolites are common. Small black specks, possibly consisting of a salt of manganese, are sometimes present.

The second type of dolostone is light in weight, cellular and therefore very porous. The rock is seen to be composed of numerous minute cells occasionally accompanied by larger examples. These minute cells make up a high proportion of the volume of the rock, the remainder of which is composed of finely granular crystalline material. Microscopical examination demonstrates that these rocks were originally ooidal. The ooids appear to have been dissolved away thus giving a cellular structure, modified by recrystallisation of the matrix during dolomitisation.

The Wetherby and Sprotbrough Members are separated by the Hampole Discontinuity, recognised locally at outcrop as a minor erosional surface with alteration of the dolostone below it. It is particularly seen around Hampole, Cadeby and Sprotborough where it is well exposed in quarries and railway cuttings. The **Hampole Beds** lie mainly above the discontinuity and comprise a sequence up to 1.5 m thick, composed of three thin, greenish, fissile mudstones separated by two cream, finely ooidal and partly laminated calcitic dolostones.

3.5.3 The Edlington Formation (formerly the Middle Permian Marl) [D61-New Edlington Brick Pit; D31- Leys Hill Bridge]

The Edlington Formation is infrequently exposed to the east of the outcrop of the Cadeby Formation. It usually occupies a belt of low lying, wet ground rising up to the escarpment of the Brotherton Formation and, as seen at Skelbrooke, Skellow, Edlington, Wadworth and Tickhill, it yields heavy, typically reddened soils.

It comprises a sequence of red and subordinate greyish green, locally dolomitic, calcareous and gypsiferous mudstones and siltstones. Where it is exposed in railway cuttings, drainage ditches and water logged and overgrown brick pits (D61), fibrous gypsum layers can occasionally be seen. This and the interbedded gypsum was once used to make plaster of Paris.

The Edlington Formation shows thickness variations of up to 6 m, with the most marked thinning frequently corresponding with a thickening of the Cadeby Formation below and vice versa, thus suggesting that the Edlington Formation fills hollows in the surface of the Cadeby Formation, where it was deposited in transient lagoons on a wide coastal plain.

From the evidence of boreholes and colliery shafts, the formation is seen to contain increasing amounts of nodular and layered anhydrite to the north and east of its outcrop, where these are concentrated at certain stratigraphical levels and are considered to be distinct formations in their own right. Although they make no contribution to the landscape, they provide good evidence of the geological history of the region, especially the changes in sea level, increasing salinity, aridity and evaporation that took place in the ancient Zechstein Sea. These are briefly summarised below:

'Marl' between Cadeby Formation and ?Hayton Anhydrite

Comprises argillaceous reddish, calcareous mudstone, with some gypsum or anhydrite as seen in Thorne Colliery No.1 Shaft. The question mark preceding the name indicates the unit is tentatively correlated with the Hayton Anhydrite.

?Hayton Anhydrite

This unit is recorded as being 13 m thick in the Thorne Colliery Centre Borehole and comprises reddish to grey anhydrite with various amounts of gypsum, dolostone, calcareous mudstones, siltstone and mudstone.

Kirkham Abbey Formation

A thin limestone, the feather edge of which may occur in the district, based on evidence from the east of Doncaster but has not been fully proven in recent boreholes.

'Marl' Between ?Hayton Anhydrite and ?Fordon Evaporites

Grey and blueish mudstones and siltstones containing lenses of anhydrite have been proven in Thorne Colliery No. 1 Shaft.

3.5.4 Brotherton Formation (formerly Upper Magnesian Limestone) [D51- Hexthorpe Flatts – The Dell]

The Brotherton Formation is a relatively uniform sequence of white to grey, mainly dolomitic limestones 13 – 16 m thick, producing a minor feature along much of the outcrop which stretches from Burghwallis in the north to Tickhill in the south and coincides approximately with the line of the A1.

The limestone is always thin-bedded and flaggy, with individual beds varying somewhat in thickness but seldom exceeding 100 mm. Such thicker beds as are present never approach the size of those in the Cadeby Formation and this is a distinguishing feature. Much of the sequence is finely crystalline and small-scale cross-bedding, ripple-bedding and channel cut and fill structures testify to shallow water deposition. Ooid-limestones are present in some western locations and are considered to be near-shore sediments. In more eastern areas the highest strata are locally algal-laminated, suggesting an epitidal environment.

Especially in the upper beds, the bedding-planes may be coated with thin films of red or grey calcareous mudstone or form distinct red mudstone partings. A local development at the base of the Brotherton Formation is a sandy dolostone resembling that found in a similar position beneath the Cadeby Formation.

Fossils are rare and are concentrated in certain beds and include algae, bivalves and some gastropods that are tolerant to saline conditions, however, the formation does contain abundant filaments of the alga *Calcinema permiana*, which allow it to be easily identified. These filaments look like thin matchsticks and are commonly present as concentrations in the cross-bedded units.

3.5.5 The Roxby Formation (formerly Upper Permian Marl)

Despite being 28 m thick at outcrop near Askern, 18 – 20 m at Bentley and 14 m in Doncaster, the Roxby Formation is very poorly exposed and thins considerably to the south, where it eventually passes laterally into the Lenton Formation, in Nottinghamshire. It is seen in sections exposed by limestone quarrying or old brick pits, at Skelbrooke and Balby respectively, where the sequence comprises reddish and greenish grey mudstone and siltstone, containing thin lenses of anhydrite and/or gypsum in places. Like the Edlington Formation it is evidenced by heavy, reddened soils.

Also like the Edlington Formation it originated mainly as fluvial and lagoonal sediment, deposited on a wide coastal plain and possesses very similar characteristics, including the development of distinct deposits, indicating hypersaline conditions and intense evaporation; these are proven in boreholes and colliery shafts showing that the units thickens away from the district to the north east. Like those of the Edlington Formation, the deposits seen deeper in the basin provide good evidence of the geological history of the area and are summarised below:

‘Marl’ between Brotherton Formation and Billingham Main Anhydrite

Comprises grey-green and red-brown silty calcareous mudstone as proved in the Thorne Colliery Centre Borehole, with gypsum veins and layers up to 30mm thick in places.

Billingham Main Anhydrite

This formation is laterally impersistent and in many places is not recorded in boreholes and has a maximum thickness of 4.6 m where found near Askern. It comprises grey anhydrite, with grey and white gypsum and is commonly associated with grey and red calcareous mudstone, particularly in the west.

Carnallitic Marl

The Carnallitic Marl is a sequence of red and subsidiary greyish green mudstones and siltstones, less than 5 m thick where recorded in the Austerfield area and at Rossington Colliery it may be less than 2.5 m thick.

Upper or Sherburn Anhydrite

Where found in the Hatfield Moors No.1 and No.2 boreholes, it is described as white, clear, translucent and finely crystalline in the Thorne Colliery Centre Borehole, it is 5.4 m thick and pearly white with red calcareous mudstone layers up to 80 mm thick.

3.6 TRIASSIC

3.6.1 Sherwood Sandstone Group (formerly Lower Mottled and Bunter Sandstone) [D101- Dunsville Quarry; D102- Common Lane Quarry; S190-92- Blaxton Common]

The Sherwood Sandstone Group occurs at or very near to the surface to the east of the A1 where landforms such as the Rossington and Doncaster ridges provide the largest outcrops. Here the sandstone weathers to form pale brown, light, sandy soil. Except for these and small areas north and east of Tickhill (Lenton Formation), where there is a pronounced scarp slope, the Sherwood Sandstone is overlain by loosely consolidated Quaternary sediments but is frequently exposed in sand and gravel pits, notably around Balby, Dunsville and Austerfield.

The Sherwood Sandstone Group in the south of the Doncaster area is subdivided into two formations, the lower unit is the Lenton Formation of probable Permian age and it is overlain by the Nottingham Castle Sandstone Formation of Triassic age. In the north of the area the Sherwood Sandstone Group is mainly covered by thick Quaternary deposits and is undivided. A borehole at Bentley towards the west of the outcrop proves 35 m of sandstone, but at Hatfield Moors and Misson, this increases to 260- 280 m. In the east where the Sherwood Sandstone is overlain by younger Triassic sediments, just east of the borough at Misterton, it has a full thickness of over 400 m.

The Sherwood Sandstone consists mainly of red, brown, fine to medium grained cross-bedded sandstone. Green-grey varieties are occasionally found and thin layers and lenses of brownish red and greenish grey mudstone and siltstone are common. It is moderately hard to friable, well to poorly sorted, and contains scattered, but locally numerous, rolled fragments of reddish and greyish mudstone and siltstone rip-up clasts. Although subangular to subrounded grain shapes predominate in the sandstone, the localised occurrences of rounded grains, and also of ventifacts and desiccation cracks, testify to some degree of aridity, with some wind blown deposits formed on dry land.

The Sherwood Sandstone is unfossiliferous. The Lenton Sandstone is interpreted as aeolian with minor fluvial interludes. The Nottingham Castle Sandstone represents a fluvial sequence deposited along the western margin of the Southern North Sea Basin as a major braided river system sourced from northern France The deposits suggest continuing, but spasmodic, uplift of the London - Brabant Massif, a large landmass that lay to the south in Permo-Triassic times.

3.6.1.1 Lenton Sandstone formation

The Lenton Sandstone Formation crops out to the north and south of Tickhill. It consists mainly of red-brown and buff mottled, very fine- to medium-grained, argillaceous, cross-stratified sandstone with subordinate beds of red-brown mudstone and conglomerate.

3.6.1.2 Nottingham Castle Sandstone formation [D44-Cedar Road Adventure Playground]

The Nottingham Castle Sandstone Formation Sandstone overlies the Lenton formation and consists of, pinkish red or buff-grey, medium- to coarse-grained, pebbly, cross-bedded, friable sandstone with subordinate lenticular beds of reddish brown mudstone. The pebbles die out north of Doncaster and hence the formation is not recognised.

3.6.2 Mercia Mudstone Group (formerly Keuper Marl)

This thick sequence of mainly reddish mudstones and siltstones, with occasional gypsum dolostone, succeeds the Sherwood Sandstone Group. The earliest deposits represent deposituion on abroad alluvial plain, with a complex association of channel sandstones, overbank deposits, lacustine and lagoonal environments. Later, the Mercia Mudstone became a desert-sabkha association, dominated by wind blown dust deposition with periodic flash floods deposited on a coastal plain around the western margin of the Southern North Sea Basin.

In Doncaster, they occupy a very small area on the eastern boundary and, being covered in Quaternary sediments, are exposed only in excavations.

3.7 NEOGENE (QUATERNARY)

The superficial deposits in the area mainly represent the deposits from at least the last two ice-ages and the intervening interglacial deposits (Figure 6). The landscape has been subjected to several episodes of erosion and several episodes of deposition. The lateral extent and thickness of the Quaternary is extremely variable and many of the sedimentary deposits possess very similar lithologies that are not easily distinguished.

The soft and unconsolidated nature of the sediments mean that they do not form easily recognisable outcrops and details of much of the geology is known from boreholes, excavations, cuttings and particularly from the temporary exposures seen in the numerous sand and gravel pits found in the area. Much of the natural landscape and topography is obscured by sand and gravel workings, but detailed field surveys reveal a wide variety of low lying landforms and structures associated with these recent geological events. The superficial geological sequence is shown in Table 1.

Series	Stage	Group	Generic Name	Thickness	Details
Holocene	Recent		Warp (1)	Up to 1m	Made ground formed by flooding land and the artificial deposition of laminated silt and clay.
	Flandrian	Yorkshire Catchment Subgroup	Peat (2)	0-4.5m	Peat
			Alluvium (3)	3-8m	River flood plain deposits
			Blown Sand (4)	0- 4m, 8 in places	Fine-grained wind-blown sand that commonly underlies peat in the east of the area
Late Pleistocene	Probably late Devensian	Caledonia Glacigenic Group	River Terrace Deposits (5)	0-8m, 15 in places	Sand and gravel with some clay
	Devensian (glacial and pro-glacial deposits)		Head (6)	0-3m	Generally sandy and gravelly clay, dependent on the surrounding deposits, caused by solifluction during and at the end of the last glacial interval.
			Glaciolacustrine Deposits (sand) (7)	0-1m	Sand with silt and clay deposited in the Pro-glacial Lake Humber or when the lake had just drained.
			Glaciolacustrine deposits (silt and clay) (8)	0-8m	Also called the Hemingbrough Formation or 25ft Drift (silt and clay) Pro-glacial lake deposits formed in Lake Humber when the present estuary was blocked with ice.
			Glaciolacustrine deposits (basal sand) (9)	0-3m	Sand with clay and silt
			Glaciofluvial deposits (10)	0-5m	Sand and gravel, with silt and clay interdigitating with Glaciolacustrine deposits in places.
	Ipswichian	Albion Glacigenic Group	Older River Gravel (11)	5-15m	Sand and gravel
Middle Pleistocene	Pre-Ipswichian possibly Anglian		Glaciofluvial deposits (12)	0-16m generally 0-10m	Well-sorted sand and gravel with abundant pebbles derived from the Sherwood Sandstone Group bedrock.
	Possibly Anglian		Older Till (13)	0- 9m	Sandy clay, with boulders, cobbles and gravel deposited from ice.
	Pre-Anglian or Anglian		Buried Channel Deposits (14)	Up to 58m	Deposits filling deep incised buried valleys; mainly sand and gravel at base overlain by thick laminated silt and clay.

Table 1 The sequence of superficial deposits in the Doncaster area. Numbers in the name column are used in the sections below and on Figure 2.

3.7.1 Pre-Anglian or Anglian Glacial Deposits

3.7.1.1 CHANNEL DEPOSITS (14)

The bedrock of the area is traversed by eleven deeply buried channels that are only proved in boreholes and which are mainly orientated approximately north-west to south-east, with the only exception being the most southerly, with an orientation of west to east. These are named as the

Moss, Barnby Dun Station, Arksey, Armthorpe, Wheatley Park, Bessacar, Rossington, Blackwood, Loversall, Hunster Grange and Lim Pool Channels.

The deposits filling the channels consist largely of virtually stoneless and commonly laminated greyish clay. Sand, with or without gravel and commonly containing coal particles, occurs in several channels, mainly in their lower parts and towards their eastern ends. Where pebbles are present they are mainly of Carboniferous sandstone, limestone and associated rocks, and of Permian limestone; they are commonly grooved and scratched.

The channels are unrelated to the present or any known pre-existing valleys and are believed to have been cut by powerful subglacial drainage, produced from the action of meltwater beneath advancing glaciers. The easterly or south-easterly trend of the channels, and the obviously Pennine derivation of some of the contained deposits, suggest that they probably flowed from sources high in the Pennines. Most of the channels in the district are aligned with gaps through the Permian scarp to the west and also point eastwards to the Haxey Gap south of the Isle of Axholme, so that a genetic relationship between the channels and these gaps is possible.

These are all interpreted as being pre-Ipswichian and most probably related to the Anglian glacial event.

3.7.1.2 Till (13) [D61- New Edlington Brick Pit; D51- Hexthorpe Flatts – The Dell; D44-Cedar Road Adventure Playground]

Patchy glacial till has been mapped throughout the western part of the area where it mainly forms relics sitting on slightly elevated bedrock so that it caps hills and ridges. These include isolated occurrences at Adwick upon Dearne, Skelbrooke, Braithwell and on the Rossington ridge. Around Balby and Warmsworth, much thicker and more extensive deposits are preserved in an ancient valley. On the flanks of the hills they are commonly much thinner and in the low ground they have not been recognised having presumably been eroded away.

Till (shown as boulder clay on older geological maps) consists of bluish grey to reddish brown silty and locally sandy diamicton with scattered erratics up to boulder size; it is more reddish or yellowish where weathered. The erratics are mainly of Carboniferous sandstone, siltstone and coal, and Permian limestone, with smaller numbers of Carboniferous limestone and chert, derived from the Pennines. A few erratics of igneous rocks, some recognisably from the Lake District, are also present.

On the evidence of these erratics, the ice which deposited the clay till in the district had traversed the eastern Pennine slopes, and some of it had originated or passed close to the Lake District. The stone orientations and analysis of coal erratics at Balby, and distribution of Permian erratics west of the Permian outcrops beyond the district show that most of the ice which entered the district from the north and north-west had flowed south down the Vale of York after crossing the Pennines. The sparsity of clay till, its isolation either on elevated locations or in sheltered low-lying areas, and the absence of associated glacial landforms, suggests a glaciation of considerable antiquity. The presence, locally above the clay till, of older river gravel, for which there is fossil evidence of an Ipswichian interglacial age, confirms the glaciation as Anglian.

3.7.1.3 Pre-Ipswichian, possibly Anglian Fluvioglacial Deposits (12) [D44-Cedar Road Adventure Playground; D102 Common Lane Quarry; D109-Hurst Plantation Quarry]

The fluvioglacial deposits occur in two main concentrations within the area, capping the Doncaster and Rossington ridges where they rest on bedrock and, occasionally, the underlying till. The deposits comprise beds, lenses and layers of both pebble-free sand, and gravel with a sand matrix. They are well bedded, with cross-bedding and cut-and-fill channel structures in places, and fairly well sorted, although cobbles and a few small boulders are also present.

However, the deposits vary considerably in composition across the district and imply an origin from different source rocks.

The sediments on the Rossington Ridge contain abundant 'Bunter 'quartzite pebbles whose only possible source is the Sherwood Sandstone of Nottinghamshire and the northern Midlands. In the absence of accompanying durable Jurassic rocks, flint pebbles are unlikely to have come directly from the east, and the only other source is the 'chalky' glacial deposits in the middle Trent Valley to the south.

Although the sand and gravel on the Doncaster ridge is superficially similar in composition to the clay till and glacial deposits, Carboniferous limestone, chert, Permian limestone and igneous rocks are virtually absent. Instead their constituents imply derivation from Coal Measures to the west instead of the glacial trans-Pennine origin to the north-west,.

The sedimentary features and compositions of these deposits, together with their ridge top location, which implies transport over a watershed, indicates a fluvioglacial origin with meltwater flowing from ice sheets in the south and west.

3.7.2 Ipswichian Deposits

3.7.2.1 Older River Gravel (11) [D101- Dunsville Quarry]

Large spreads of Older River Gravel are present in the north and east of the district where they form a terrace-like area with an elevation of up to 12 m above OD. They contain sedimentary structures indicative of deposition from a fluvial environment.

These deposits consist of beds, lenses and layers of well sorted fine to medium gravel with a sand matrix, without pebbles, which include level bedding and gentle cross-bedding, and also shallow cut-and-fill channel structures. They rest mainly on Sherwood Sandstone but transgress locally over clay till and glacial channel deposits. Their top, whether at outcrop or concealed beneath younger deposits, is commonly severely cryoturbated and strewn with ventifacts.

There is a wide variation in the composition of the sand and gravel and this, in addition to variations in palaeocurrent directions, indicates different geographical origins. To the north–west of Doncaster at Edenthorpe, Armthorpe and Dunsville and along the Don Valley, the pebbles mainly comprise Carboniferous sandstone and suggest deposition by fluvial activity of the river Don.

To the south-east of Doncaster at Blaxton, Finningley and Austerfield, the pebbles mainly comprise 'Bunter' quartzite, deposited by the rivers Idle and Thorne which flowed from the south.

Fossiliferous deposits within the Older River Gravel near Austerfield and Armthorpe have provided good evidence of the palaeoenvironment. Wood fragments, fruits, pollen and seeds indicate oak, pine, hazel, birch and alder in a temperate environment. Other non-tree pollen suggest freshwater and saltmarsh habitats, with dinoflagellate cysts and forams also implying an estuarine tidal reach.

3.7.3 Devensian Deposits

The Devensian cold Stage started approximately 120 000 years ago and, using modern radiocarbon dating techniques, is considered to have ended about 10 000 years ago.

During this time, the region was subjected to severe periglacial conditions when the land was generally deeply frozen. At the start and end of the Devensian Stage, there are distinctive sedimentary and topographical structures that are termed the **Lower and Upper Periglacial Surfaces**.

Four types of non depositional evidence reflect these conditions. They are cryoturbation structures, alases, ventifacts and desert pavements and all are important features that have enabled geologists to interpret climatic conditions throughout the northern hemisphere.

Cryoturbation structures are subsurface disruptions resulting from freezing and thawing of groundwater in what is called the active layer. Alases are wide, shallow, steep-sided, flat-bottomed depressions, commonly circular or oval in shape, as seen in the West Moor depression. Ventifacts are stones, generally of large pebble size or bigger, that have been shaped by prolonged impact of wind-blown sand grains and possess flat facets with sharp edges. Desert pavements are the remnants of rock debris after lighter particles have been blown away by wind.

Position of Lower Periglacial Surface

3.7.3.1 Glacial sand and Gravel (10)

Small outcrops of glacial sand and gravel run in a line from Thorne to Wroot. The deposits contain pebbles consisting mainly of Carboniferous sandstone and Permian limestone, with a few of other Carboniferous rocks including limestone and chert, and rare Lake District rocks, indicating a provenance from the north-west.

The deposits share their stratigraphical position between the two periglacial surfaces with the lacustrine sand and gravel which, as described below, were formed in and around Lake Humber when at its maximum level of about 30 m above OD in the late Devensian. It is highly probable that the ice surged transiently into the lake and deposited sand and gravel, mainly along its western and southern edges, as it melted.

3.7.3.2 Lacustrine Sand and Gravel Deposits (9)

Sand and gravel deposits with compositions similar to older sediments described above occur throughout the area, but are not detailed on the current geological map.

Around Burghwallis, Cusworth and Askern, these comprise angular to subrounded pebbles of Permian limestone in a grey silt matrix and at Bentley, there are also Carboniferous rocks. Further south, at Rossington, Bawtry and Austerfield, as seen in sand and gravel pits, there is a predominance of ‘Bunter’ quartzite pebbles.

These deposits indicate an origin by reworking of pre-existing deposits in situ, with no input of sediment from outside the immediate locality and imply deposition as beach deposits at the edge of Lake Humber. Throughout the district, these deposits occur at 27 m OD and it is a striking fact that dry valleys, which are frequent in the Permian limestone, all terminate at about this level.

3.7.3.3 Glaciolacustrine Deposits (silt and clay) (8)

Known previously as the 25 Foot Drift but now termed the Hemingbrough Formation, this vast expanse of loose, unconsolidated sediment forms most of the flat plain of the southern part of the Vale of York that, in Doncaster, covers most of the low lying areas or flat land east of the A1.

It essentially comprises a sequence of silt and clay with some fine grained sand deposited in and at the edges of Lake Humber, which was formed as the result of a blockage of the established river drainage system by an ice sheet that had encroached from the north-east. The details of this important period in Doncaster’s recent geological history need to be the subject of extensive field survey work and research but a brief summary of knowledge acquired to date is as follows:

Silt and Clay: These beds comprise fine grained grey to red sediment with low-angle cross-bedding and ripple structures that contain virtually no stones. The sporadic stones that do occur are ‘drop stones’ that have been deposited from melting ice.

Marginal Sand: The sand is fine and rarely medium grained, often with silt, clay, abundant coal particles and, in some areas, a few small pebbles.

It is often not easy to distinguish either of these, as they pass laterally into one another but they were both formed in a relatively placid environment, undisturbed by the influx of high energy, rapidly flowing rivers.

3.7.3.4 Glaciolacustrine Deposits (sand) (7)

Resting on the deposits described above, sand forms discontinuous, low ridges and mounds around Hampole Beck, Braithwaite and Fishlake, with silt, clay and coal particles at their margins. Many of these landforms are adjacent to present rivers and suggest that these are levees which indicate that Lake Humber had partly filled with sediments and drained so that rivers, now recognisable in modern times, had begun to make their mark on a flood plain. An increasing abundance of sand dunes indicates the action of wind upon an increasingly dry land surface and many of the deposits can be interpreted as fluvio-aeolian.

3.7.3.5 Head (6) [D20–22- Cadeby Cliff/Constitution Hill; DR4-Nearcliff Wood Quarries]

Head deposits are mainly associated with the older Quaternary deposits or with exposed bedrock within the area. They are generally unsorted gravels and clays that are the product of reworked local glacial and fluvioglacial sediments. They are found in valley bottoms and generally represent re-deposition of material, by freeze and thaw conditions (solifluction) and hillwash in a periglacial environment.

3.7.3.6 River Terrace Deposits (5)

River terrace deposits are present in the north-west of the area near Bentley and around the river Don, where the clast component is predominantly of Carboniferous rocks. Further to the south-east, especially at Austerfield, quartzites derived from the Sherwood Sandstone Group are the main constituent. Together, these sediments are intimately linked with events that were taking place in the Vale of York and terrace river valleys.

Position of Upper Periglacial Surface

3.7.4 Flandrian Post-Glacial Deposits

3.7.4.1 Blown Sand (4)

Blown sand is extensive in the north-east of the district, where it forms thin spreads of fine-grained silty sand, but much is largely concealed beneath and alluvium. It is characterised by its fine-grained, well-sorted nature and forms linear and crescentic dunes, often with horns that provide evidence of the wind direction. The sand is often associated with the formation of river levees and these are seen along the River Torne from Auckey Common to Wroot.

The sand overlies both Sherwood Sandstone and glaciofluvial sediments and was formed after Lake Humber drained and dried up.

3.7.4.2 Alluvium (3)

Extensive areas of alluvial deposits are present in the area associated with all the main drainage courses. In the Doncaster area it is associated with the River Don, but also spreads out into low-lying area of Potter Carr to the south of Doncaster. Along the River Don, the alluvium is up to around 6 m thick. By comparison, the large ponded areas of alluvium are only 3 or 4 m thick and are mainly concentrated in a belt along the junction of the Sherwood Sandstone Group and the Roxby Formation. In the north-east of the area the alluvium associated with the east of Hatfield Moors is much thicker than the other rivers of the area and reaches around 6-8 m.

In the deeper parts of the former alluvial channels much of the deposit consists of sand and silt, commonly with a gravelly base. The alluvium becomes increasingly clayey upwards; the surface deposits of the major rivers consist of silt, but this grades away from the rivers into stiff, heavy and commonly peaty clay. The upward-decreasing coarseness of the alluvium reflects decreasingly energetic fluvial deposition in the incised river courses as sea level rose rapidly in the Humber region during the Flandrian. After the incised courses were filled with alluvium, deposition culminated in thin but extensive spreads of appreciably peaty clay and peat on adjacent low-lying areas.

3.7.4.3 Incision and Denudation

Contours at and below OD on the base of the Flandrian deposits reveal a landscape in which rivers crossing the district, including minor ones, have deeply incised their courses, reaching depths of nearly 20 m below OD as they approach the Humber Gap. This vigorous fluvial incision was accompanied by little or no interfluvial erosion. It resulted from a rapid drop of regional drainage base level, when the ‘nickpoint’ of the ‘River Humber’ finally eroded through the glacial deposits in the Humber Gap to reach the soft, waterlogged sediments of the Hemingbrough Formation to the west.

3.7.4.4 Peat (2)

Peat is extensive in the east of the area, where it forms spreads resting on the flat Glaciolacustrine deposits. The peat is rarely more than a few metres thick, but on Hatfield Moors and Thorne Moors, where it has been extensively worked, it is in excess of 3 m thick. It is also commonly associated with present and past drainage courses in the centre and west of the area, notably along the length of the River Torne. A significant deposit also occurs in the West Moor depression.

The peat growth may be attributed mainly to two factors. One is the wetter climate which ensued from Atlantic times onwards, and which, particularly from the onset of Sub-Atlantic times, was conducive to raised bog development in suitable areas. The other is the waterlogged ground and poor drainage in low-lying areas produced in late Flandrian times in the Humber region by the change of sea level, which rose sharply from about 9 m below OD to between 3 m and 5 m below OD between 7000 and 6000 radiocarbon years ago, but which has oscillated within a metre or two of OD within the last 3500 radiocarbon years.

3.7.4.5 Warp (1)

Warp or “floodwarp” develops by building flood banks around field areas and artificially flooding the ground so that layers of clay and silt are built up. Over time the land can be raised by a metre or so. This can be seen around Thorne Moors. In several places on Hatfield Moors “cartwarp” has been deposited. This term refers to the process of raising the level of the land manually by transporting material into the fields and spreading it out.

3.7.4.6 River Diversions

Several man-made river diversions are recognisable in the district, partly by comparing the early Flandrian courses with the present courses.

A side branch of the River Don, formerly known as Turnbrigg Dike, was constructed northwards from Thorne to the River Aire near East Cowick, at some time before 1410 beheading the lower course of the River Went at a locality which is now their confluence, south of New Bridge. The drainage alterations accomplished by Cornelius Vermuyden in 1625-27 consisted essentially of diverting two rivers. The River Torne, having previously joined the Idle near Tunnel Pits Farm, was channelled into an artificial course, the New River Torne, which joins the Trent outside the district at Althorpe.

3.8 STRUCTURE

Towards the end of the Carboniferous period, during the hiatus between Coal Measures deposition and the renewal of sedimentation in the late Permian Zechstein Sea, the Hercynian Orogeny produced gentle folding, extensive faulting, uplift and consequent erosion in the region.

In general, the pattern of folding is aligned north-west to south-east with Carboniferous strata dipping gently to the north-east, reflected in the dip and scarp topography that can be seen in exposed Coal Measures in western Doncaster to the north of the River Don. Geophysical evidence and detailed mapping of the concealed Carboniferous strata during exploration of the coal fields reveals similar trends, with the major structures being principally the Finningley syncline, the Askern-Spital anticline, with smaller similarly aligned structures to the north.

The exception is a narrow belt that extends from Rotherham to Mexborough and Cadeby, associated with the Don Monocline, which runs from the south-west to north-east and where, locally, the strata dip as much as 30 degrees to the south-east. At Denaby, this is evidenced by small but very distinctive landforms with steep dip and scarp topography.

The pattern of faulting follows the general plan common in the coalfield, in which two sets of faults at right angles and trending respectively north-west and north-east may be recognized. In the area as a whole there is nothing to choose in importance between the two groups.

However, a belt of parallel faults trending north-eastwards, associated with the Don Monocline, have had a considerable influence on the geology and topography of the region. The most persistent of these is the South Don fault (Figure 4) which is evident at Conisbrough, Cadeby and Cusworth and has been located at several places in Thorne Colliery; it can also be traced on the NEXTMap image (Figure 9). South-east trending faults are notable along the Askern-Spital structure but whilst once important to the collieries do not greatly affect the topography of the area.

Along the limestone escarpment, particularly at Hampole, Bilham and Conisbrough, overlying Permian strata have been displaced by these faults. These along with rift, or graben, structures around Warmsworth, Balby and Loversall, in which Triassic sediments were laid down, show that movement often continued into Permian and Triassic times. The rift structures around Loversall are also associated with movement along south-east trending faults along the axis of the Finningley Syncline, where there is evidence that this area was also subjected to crustal tension and subsidence.

The Permian rocks rest with marked unconformity on the underlying Coal Measures and although local variations relate to earth movements that affected Carboniferous rocks, they generally have a very shallow dip to the east or north-east. Along with the overlying Triassic rocks that possess a similar dip this may partly be attributable to the continuing tilting and subsidence of the Southern North Sea Basin in which the Zechstein Sea was formed. However, evidence from younger strata to the east of the district shows that there were unrelated earth movements during the Jurassic period and post-Cretaceous times and that the dip of the Permo-Triassic rocks is probably best considered as a composite structural feature.

4 Mineral Resources

4.1 INTRODUCTION

The earliest records of exploitation of a geological resource in Doncaster, other than water supply, refer to peat cutting, which has continued from mediaeval times and was until recently carried out on a large scale by mechanised means. In contrast, the sand and gravel industry has expanded enormously since the Second World War. However, the most important industry based on a geological resource is coal mining. This began in the first decade of the 20th century with the sinking of several deep shafts, forming part of the extension of the Yorkshire Coalfield eastward into its 'concealed' region. This industry, more than any other, has been responsible for the large increase in population in the district, mainly concentrated in Doncaster and adjacent areas, during the present century, and it has enabled other industries to develop in these areas. More recently there has been some exploration for deep hydrocarbon sources in the district, and although the results are extremely modest by comparison with other regions in and around Britain, the gas find which produced a spectacular 'blow out' on Hatfield Moors late in 1981 has now been tapped for industrial use.

4.2 RESOURCES AND RESERVES

Mineral resources are natural concentrations of minerals or bodies of rock that are, or may become, of potential interest for the economic extraction of a mineral product. They exhibit physical and/or chemical properties that make them suitable for specific uses and are present in sufficient quantity to be of economic interest. Areas that are of potential economic interest as sources of minerals change with time as markets expand or contract, product specifications change, recovery technology improves or more cost-effective sources become available.

That part of a mineral resource, which has been fully evaluated and is commercially viable to extract is called a mineral reserve. In the context of land-use planning, the term mineral reserve should strictly be further limited to those minerals for which valid planning permission for extraction has been granted (i.e. permitted reserves). Without a valid planning consent no mineral working can take place and consequently the economic value of the mineral resource cannot be released.

Currently active, ceased and recently disused mines and quarries from the BGS BritPits Database are shown on Figure 10.

4.3 SAND AND GRAVEL

Sand and gravel resources occur in a variety of geological environments. In the Doncaster area these resources occur mainly within superficial deposits, resulting from glaciofluvial, glaciolacustrine, fluvial and aeolian processes. Additional sand and gravel resources occur within the bedrock.

Sand and gravel are defined on the basis of particle size rather than composition. In current commercial practice, following the introduction of new European standards from 1 January 2004, the term 'gravel' (or more correctly coarse aggregate) is used for general and concrete applications to define particles between 4 and 80 mm, and the term 'sand' for material that is finer than 4 mm, but coarser than 0.063 mm. For use in asphalt 2 mm is now the break point between coarse and fine aggregate. Most commercial sand and gravel is composed of particles that are rich in silica (quartz, quartzite and flint).

4.3.1 River sand and gravel (Terrace and sub-alluvial deposits)

Resources occur in both raised river terrace sequences flanking the modern floodplains and in floodplain terrace deposits underlying present day alluvium. This sequence of deposits is best developed along the River Don with a succession of deposits formed, representing accumulations of sand and gravel in response to falling sea level in Pleistocene times.

Extensive terrace deposits occur around Bentley at up to 12 m above OD. These deposits consist of sand, thin beds of fine gravel in which most of the pebbles are of Carboniferous rocks, and thin clay beds. Coal particles are present in the sand fraction. The deposits pass laterally into glaciolacustrine silt and clay deposits. East of Doncaster, fluvial deposits of sand and gravel form extensive flattish spreads, commonly referred to as Older River Gravels. These deposits consist of beds, lenses and layers of both pebble-free sand and well-sorted fine to medium gravel with a sand matrix. Variations in composition of the gravel fraction show that the more northerly deposits around Dunsville were derived from the west, presumably via the Don, with the predominant composition of the pebbles being Carboniferous sandstone. In areas rich in Carboniferous-derived materials, coal detritus, usually in the form of coarse sand-sized particles can comprise up to 1 per cent of the deposit.

The Older River Gravels are worked for sand and gravel at several sites in the Doncaster district, primarily in the Finningley area and to the northeast of Doncaster for example, at Dunsville Quarry. At both Finningley and Austerfield Quarries, Older River Gravels, the original focus of extraction, have now been depleted. Current extraction at Finningley is from adjacent glaciofluvial deposits while extraction at Austerfield is now from the underlying Sherwood Sandstone Group.

Sub-alluvial gravels are encountered beneath the alluvium of the major valleys throughout the area. The extent of alluvium has been modified in places by land management practices, including the construction of drainage channels and the deposition of Warp (silt and clay) during periods of artificially controlled flooding. The deposits are compositionally similar to the river terrace deposits. They were mainly laid down during periods of deep downcutting during the late Devensian cold phase when sea-levels fell to at least -100 m OD. The subsequent rise in sea level enabled silting up of these river channels producing thick overlying alluvial deposits. The deposits rest on an irregular channelled surface and are thus of very variable thickness. These deposits are always saturated and require wet working.

4.3.2 Glaciofluvial deposits

The sequence of glaciofluvial deposits is complex with units commonly exhibiting intricate relationships. Bodies of sand and gravel may occur as sheet-like layers or ridges on top of the sheet of till (boulder clay) or as elongate, irregular lenses within the till sequence. Areas of wholly concealed, and thus unknown, bodies of sand and gravel may occur under spreads of till and other drift deposits.

Glaciofluvial deposits occur in the east of the county, where they form elongate ridges and mounds capping the Doncaster and Rossington ridges and adjacent hills. These deposits have been described in detail in BGS Mineral Assessment Reports Nos. 37 and 92. The deposits comprise beds, lenses and layers of both pebble-free sand, and gravel with a sand matrix. They are fairly well sorted, though a few cobbles and small boulders are present. The deposits rest mainly on Sherwood Sandstone and transgress locally over clay, till and glacial channel deposits.

4.3.3 Glaciolacustrine deposits

During the Devensian glaciation, ice occupying the present coastal zone farther east blocked the eastward-draining valleys including the Humber Gap between Brough and Winterton and thus impounded ‘Lake Humber’ in the southern part of the Vale of York. Glaciolacustrine deposits associated with this glacial lake occupy a wide irregular channel incised into Older River Gravels (see River sand and gravel) and Sherwood Sandstone, running from Doncaster Racecourse northeastwards towards Hatfield Woodhouse. They are present in the West Moor depression, in other low-lying localities towards the east (where they pass under the peat on Hatfield Moors) and under the alluvium of the River Don in the northwest. These deposits are predominantly bedded fine-grained sands and laminated clays up to 5 m in thickness. The sand fraction is predominantly fine-grained quartz; up to 35 per cent of medium-grained sand has been recorded but coarse-grained sand nowhere accounts for more than 1 per cent of these deposits.

4.3.4 Blown sand

Blown sand deposits occur in the east of the area and are largely concealed beneath peat and alluvium. The most extensive blown sand deposits crop out on the flanks of Thorne Moor, Hatfield Moor and south of Finningley. Extensive deposits of sand, that rest in turn on glaciolacustrine silt and clay, also extend under the peat and alluvium of Thorne Moor and adjacent areas. This concealed sand varies from 0 to 3 m in thickness, with appreciable variations across short distances due to its undulating top. Blown sand is not worked in the area. These deposits are believed to be largely of late Quaternary age resulting from aeolian reworking of fluvial and glaciofluvial sands, particularly those associated with the Vale of York superficial deposits.

4.3.5 Bedrock Sand and Gravel

The sandstones and conglomerates of the Sherwood Sandstone Group, in particular the Nottingham Castle Sandstone Formation, have been worked mainly as a minor component in the floor of sites working overlying superficial sand and gravel deposits. This material is mainly friable, loosely consolidated and easily worked. It is largely composed of a fine "clayey" sand with generally <2 per cent gravel and is generally more suitable for building sand and asphalting than the 'sharper' alluvial sands which are used for concreting. Where more gravel is present or conglomeratic horizons occur, the clasts are mainly rounded and sub-rounded quartz and quartzite pebbles with subordinate Carboniferous sandstone fragments. The Sherwood Sandstone Group is currently worked at Austerfield Quarry. The sand, which is dry screened, is predominantly used for mortar sand and asphalt sand and to a lesser extent for fill and pipe bedding sand.

4.4 CRUSHED ROCK AGGREGATES

A variety of hard rocks are suitable for use as aggregates when crushed. Their suitability for different applications depends on their physical characteristics, such as resistance to impact and abrasion and crushing strength. Higher quality aggregates are required for coating with bitumen for road surfacing, or for mixing with cement to produce concrete. For applications with less demanding specifications, such as constructional fill and drainage media, lower quality materials are acceptable. The only significant source of crushed rock aggregate in Doncaster is dolostone.

4.4.1 Dolostones

Dolostones and subordinate limestones of the Zechstein Group occupy a broad outcrop of easterly dipping strata to the west of Doncaster (Figure 3). These strata, commonly referred to as the Magnesian Limestone, have highly variable lithological and rock properties. They are frequently too weak and friable to make high quality aggregate. Nevertheless, they are extensively quarried for low-grade applications, such as sub-base roadstone and fill, but some of the rocks are sufficiently strong and durable to be used as concreting aggregate or coated roadstone.

4.4.2 Sandstone

Most sandstone is too weak and porous to make good quality aggregate for roadstone and concrete, but may be suitable for fill or for the production of sand for reconstituted stone products.

Sandstones form substantial parts of the Upper Carboniferous sequence in Doncaster where they are interbedded with mudstones and coals. Where thick beds of sandstone are developed they have been widely extracted for building stone, although there is little current quarrying activity. There is no production of aggregate materials due, in part, to more readily available local supplies of crushed dolostone and natural sand and gravel.

4.5 INDUSTRIAL DOLOSTONE

Dolostone is an important economic mineral because of its physical and chemical properties. It has a wide variety of applications but its primary use is in the construction industry. Dolostone is also important in certain industrial applications where its chemical properties are important. The principal uses of industrial dolostone are as a flux in steelmaking, for refractory use and in glassmaking. For these applications, dolostone is required to be of high chemical purity. Dolostone for industrial purposes accounts for a relatively small and decreasing proportion of total dolostone output in Britain.

Dolostones with sufficiently low levels of impurities to be used in steelmaking and glassmaking are relatively scarce in Britain. The Permian, Cadeby Formation in the Cadeby, Sprotborough and Warmsworth area is, however, of higher purity and is extracted for glassmaking at Warmsworth and Cadeby quarries. The quality of the stone is variable and selective quarrying of specific horizons and subsequent blending is required to ensure that the stone meets the low iron requirements for glassmaking. Ground dolostone is also used for filler applications.

4.6 BRICK CLAY, INCLUDING FIRECLAY

'Brick clay' is used in the manufacture of bricks, roof tiles, clay pipes and decorative pottery. These clays may sometimes be used in cement manufacture, as a source of constructional fill and for lining and sealing landfill sites. The suitability of a clay for the manufacture of bricks depends largely on its behaviour during shaping, drying and firing. This determines the properties of the fired brick, such as strength and frost resistance and, importantly, its architectural appearance.

Most facing bricks, engineering bricks and related clay-based building products are manufactured in large automated factories. These represent a high capital investment and are increasingly dependent, therefore, on raw materials with predictable and consistent firing characteristics in order to achieve high yields of saleable products. Blending different clays to achieve improved durability and to provide a range of fired colours and textures is an increasingly common feature of the brick industry. Continuity of supply of consistent raw materials is of paramount importance.

The major brick clay resources in Doncaster occur within the mudstones of the Pennine Coal Measures Group which are interbedded with siltstones, sandstones, coal seams and seatearths. The mudstones are dark grey, with variable carbon content. They are typically up to 5 m thick, but much thicker (20 to 30 m) in places.

Fireclays typically occur beneath coal seams and resources are confined to coal-bearing strata. Although originally valued as a refractory raw material, fireclay is now used by the brick industry for its combination of good technical properties allied to its cream-buff-firing characteristics. Not all fireclays are suitable for buff brick production because of the presence of impurities. The close association of fireclay and coal means that opencast coal sites are one of the few viable sources. Resources of fireclay are thus coincident with opencast coal resources and consequently the future supply of fireclay is largely dependent on the future of the opencast coal industry.

4.7 BUILDING STONES

The Pennine Coal Measures Group has been a prolific source of building sandstones, and the many sandstones that occur in the succession have all been used for local building purposes, mostly to the west of Doncaster around Barnsley, Mexborough, Sheffield and Rotherham.

The pale coloured dolostones of the Cadeby Formation have been extensively quarried for local building along much of their outcrop, most notably around Brodsworth, Doncaster and Conisborough. Building stone is largely produced as a by-product of aggregates and dolostone production but good quality stone extracted by traditional quarry methods is intermittently available.

4.8 COAL

Doncaster lies predominantly within the East Pennine Coalfield. The coal-bearing strata of the Pennine Coal Measures Group (Upper Carboniferous) generally dip to the east or south. Coal seams crop out at the surface in the west and become concealed to the east beneath younger rocks, down to depths of 1200 m below OD (Figure 10). Coal seams are numerous and many are developed at a regional scale. They vary laterally in both thickness and composition, chiefly by variation in the number of dirt partings present within the seams. Nine major coal seams are recognised in the Pennine Coal Measures Group of the Doncaster area. The seams are mainly bituminous and the calorific value and rank of the coals broadly increases eastwards. Sulphur is an impurity associated with all Yorkshire coals, with the most easterly parts of the coalfield recorded as moderately high in sulphur.

Although UK domestic production of coal has declined in recent years, South Yorkshire remains an important coal-mining region in the UK with five opencast coal sites and two deep coal mines in recent operation. In the last five years, from 1999 to 2004, total coal production in South Yorkshire decreased from 3.5 Mt to 2.8 Mt. There is no current opencast coal production in Doncaster. Production from the last underground coal mine in Doncaster, Rossington ceased in 2006.

4.9 PEAT

Peat is an unconsolidated deposit of compressed plant remains formed in a water-saturated environment such as a bog or fen. Bogs occur in areas where inputs of water (almost exclusively from precipitation) have a low nutrient content and where rainfall is sufficient and drainage low enough to maintain the ground surface in a waterlogged condition. The vegetation is characterised by acid-tolerant plant communities of which the moss genus *Sphagnum* is dominant. The two main types of bog are **raised bogs**, characteristic of flat underlying topography and found on plains and broad valley floors; and **blanket bogs**, which occur mainly in upland areas where conditions are suitably cool and wet, both of which occur in Doncaster.

Many lowland raised bogs have been designated as sites of international and national conservation importance. Peat in England is dug almost entirely (98 per cent) for horticultural purposes, either as a growing medium, or as a soil improver.

In Doncaster, extensive peat deposits occur in the east of the county on Hatfield Moors and Thorne Moors. These deposits have been exploited for many years and the industry based on these resources is currently one of the largest in Great Britain. The peat is extracted by both a mechanised block cutting method and a surface milling technique, the latter accounting for an increasing proportion of the output. The peat is used for a variety of horticultural applications. The upper part of the deposit produces a light brown, open-textured peat which is of premium quality. A darker, more compact material from lower levels is of less value. These deposits occur within designated conservation areas (SSSI, SPA and SAC). Natural England now own both Thorne and Hatfield moors and Peat extraction has now largely ceased with extraction only occurring as part of the restoration process. Natural England managed restoration programmes are now in place to return the land to its original raised bog status.

4.10 HYDROCARBONS

4.10.1 Conventional Oil and Gas

Doncaster lies towards the northwestern end of two major Carboniferous basins: the Gainsborough Trough and Edale Gulf. Within these areas source rocks were deposited which have since produced significant quantities of oil and gas, forming a series of important oil and gas fields to the southeast that make up the East Midlands Oil Province. Permian and Triassic strata crop out over the eastern half of the county providing, in addition to Carboniferous sequences, potential reservoir rocks for hydrocarbons generated from the Carboniferous rocks.

Several exploration wells were drilled in the county between 1940 and 1983 (Figure 11). All were dry, plugged and abandoned with the exception of two wells. Trumfleet 1 proved a major gas discovery but was only developed in 1998. To the southeast, Hatfield 1 followed as a gas discovery in 1981 and proved to be the discovery well for the series of wells that confirmed the two related Hatfield West and Hatfield Moors gas fields, which were developed in the mid 1980s. Trumfleet was still producing in late 2005, whilst the role of the Hatfield gasfields had changed to that of gas storage facilities, gas being injected into the reservoir during periods of low demand and then pumped out during peak demand.

The pattern of exploration to date thus indicates that the hydrocarbon potential of the county is perhaps relatively poor, due to the previous exploration and the level of coal mining activity. As seen in the Hatfield fields, depleted oil and gas fields could be increasingly used for gas storage. The majority of the exploration licences held in the county relate to the extraction of methane (see below).

4.10.2 Abandoned Mine Methane (AMM), Coal Mine Methane (CMM) and Coal Bed Methane (CBM) Potential

Pennine Coal Measures forming crop out or are below the Permian cover in much of the area. These Coal Measures have a generally simple eastward dip with local folding. They continue eastwards beneath the Permian cover rocks in the east of the county, being continuous with the concealed Eastern England Coalfield.

The Pennine Coal Measures in the county have been very heavily worked, with thicker seams almost totally worked out. The coal across the county is a high volatile bituminous coal with a seam gas content of between 4.1 and 6.1 cubic metres methane per tonne. In the USA, most CBM production is from coals containing 7 or more cubic metres methane per tonne. The lower gas content of the coal in the county, combined with the fact that the coalfield has been heavily worked suggests that CBM development from virgin coal seams in South Yorkshire is probably not economic at present. However, the gas seam content in the South Yorkshire region is 6.1 cubic metres methane per tonne and is therefore perhaps only just marginal. Future CBM potential and prospectivity will be dependent on areas of undisturbed coal, which in the county will probably be limited to the east.

Initially AMM and CMM potential in the county appears good, given the intense coal mining in the area. During 2005 Alkane Energy held one licence (PEDL 37), Stratagas one (PEDL92) and Octagon three (PEDLs 60, 11, 43) that covered some part of the area. These permit the extraction of gas from abandoned coal mines with schemes at Wheldale (near Castleford) and at Monk Bretton (near Barnsley) and at Shirebrook and Markham in the North Derbyshire, although all are outside Doncaster. Investigations for CMM are currently taking place at Cadeby; results of this are not yet available. The gas produced is commonly used on site for power generation or supplied direct to local consumers. However, the potential for water entering and flooding areas of the mines, that are often interconnected, could impact greatly on any prospects identified in the county. Water is currently pumped from the Barnsley area to protect Maltby Colliery.

Prospects for AMM in the county are thus thought to be good if the mines are not flooded. The schemes operated by Alkane Energy have, however, seen rapid declines in the volumes of gas extracted and concerns in 2003 over the classification and tax regimes of the resource have led to doubts over the economic viability of this resource. Coal Mine Methane is recovered from existing operating mines.

A potential future area for development in coalfield areas is Underground Coal Gasification. This is very much an unproven, new technology, which is under review and test in a number of countries. Again, the level of mining across the county and the depth of the coals might rule against this being a realistic potential resource in Doncaster.

4.10.3 Licensing

The Department of Trade and Industry grants licences for exclusive rights to explore and exploit oil and gas onshore within Great Britain. The rights granted by landward licences do not include rights of access, and the licensees must obtain any consent under current legislation, including planning permission. Licensees wishing to enter or drill through coal seams for coalbed methane and abandoned mine methane must also seek the permission of the Coal Authority.

5 Groundwater Resources

5.1 OVERVIEW

The Environment Agency licence groundwater abstraction in Doncaster for a number of purposes including:

- Agricultural use, including irrigation (50 abstraction points)
- Industrial processes, including cooling (31 abstraction points)
- Public water supply (11 abstraction points)
- Mineral washing (4 abstraction points)
- Lake and pond level maintenance (1 abstraction point)

In addition, there are a number of unlicenced abstraction boreholes, mainly for domestic supplies. An extract from the BGS Wellmaster database of water wells and boreholes is shown on Figure 12; these include licenced and unlicenced wells and boreholes, and not all sources may currently be in use.

Groundwater is abstracted from a various subsurface strata within the Doncaster region, including:

- Carboniferous Limestone Supergroup (not present at surface)
- Pennine Coal Measures Group (mainly in the the Mexborough Rock)
- Permian Yellow Sands, Cadeby and Brotherton formations
- Triassic Sherwood Sandstone Group
- Quaternary superficial deposits

The most important of these aquifers are considered below. More detail is given in Allen et al. 1997 and Jones et al. 2000.

5.2 PERMIAN YELLOW SANDS, CADEBY AND BROTHERTON FORMATIONS

The hydrogeology of the Permian strata is controlled by lithology and structure. Variations in lithology result in changes in hydraulic conductivity and hence transmissivity and yield. However, the greatest control on the aquifer properties is the extent of the fracturing. As a consequence aquifer properties are unpredictable. The Yellow Sands Formation has been an important aquifer throughout the area and its presence in colliery shafts often posed considerable flooding problems for the coal mining industry. The Cadeby Formation is also a significant aquifer.

5.3 TRIASSIC SHERWOOD SANDSTONE GROUP

The Triassic Sherwood Sandstone Group is the most important aquifer in the Doncaster area. Groundwater flow is predominantly within fractures, although intergranular flow and storage is siginificant. The fluvial sequences which form most of the Sherwood Sandstone Group aquifer fine upwards from pebbly sandstone to sandstone and siltstone. Extensive mudstone horizons, resulting from the settling of flood overbank deposits, also occur. Channel deposits may be continuous for distances of up to tens of kilometres. The result of this deposition is that hydraulic conductivity in the aquifer may be directional: values are likely to be higher along and down the channels. Fine-grained layers within the sandstones have lower permeabilities, and can act as confining layers. There is a general northerly decrease in grain size due to the fact that much of the sedimentation occurred from braided rivers flowing northwards from the Armorican massif. The lateral persistence of individual fine-grained bands can be highly variable. Lateral facies changes can cause deposits to change from being aquifers to aquitards.

The water table beneath Doncaster is typically 5 to 15 m below ground level. As the aquifer is generally unconfined, the vulnerability is regarded as moderate to high. The Environment Agency considers current abstraction status to the east of the city as being unsustainable.

Doncaster's public water supply is drawn from 11 sites operated by Yorkshire Water located mainly to the east of the city. At each site there are two, or more commonly three, large diameter boreholes. These typically penetrate either close to the base or into the lowest third of the Sherwood Sandstone aquifer (with depths of 120 to 241 m). Private abstraction, mainly for industrial uses, is also from boreholes across the city and its fringes.

Following the wet autumn and winter of 2000 – 2001 water levels in many aquifers rose to exceptionally high levels and remained high for extended periods of time. Associated with this rise, concentrations of nitrate in abstracted groundwater have increased considerably. Against this background, Yorkshire Water has detected a possible upturn in trace pesticide concentrations in blended water from the Triassic Sandstone aquifer for supply in the Doncaster area. A recent programme of analysis of groundwater from individual boreholes has shown that a number have been affected by pesticides, possibly from both agricultural and amenity use.

5.4 QUATERNARY SUPERFICIAL DEPOSITS

The cover of Quaternary deposits in the Doncaster area is complex and contains a wide range of lithologies with differing hydraulic conductivities. Some provide hydraulic connectivity with the Sherwood Sandstone aquifer and others act as an aquitard. These deposits include river terraces, silts and clays, peat and alluvium. In some locations multiple lithologies are found superimposed, resulting in inter-bedded layers of varying transmissivity.

6 Geodiversity of Doncaster

6.1 SITE OF SPECIAL SCIENTIFIC IMPORTANCE (SSSI)

Four sites in Doncaster are listed as SSSIs (Figure 13):

- Ashfield Brick Pit, Conisbrough (CadebyFormation)
- Bilham Quarry (CadebyFormation)
- Cadeby Quarry (CadebyFormation)
- New Edlington Brick-clay Pit (Edlington Formation)

All four sites were cited under the Geological Conservation Review (GCR) process and the details are published in the Marine Permian of England GCR volume (Smith, 1995)

6.2 REGIONALLY IMPORTANT GEOLOGICAL/GEOMORPHOLOGICAL SITES (RIGS)

In 1997 the survey of geological sites in Doncaster by the South Yorkshire RIGS Group was essentially based on information gleaned from BGS Geological Memoirs and Maps, old Ordnance Survey maps and other relevant publications, largely provided by Doncaster Museum. The desktop research was undertaken by a small team of volunteers and enthusiastic amateurs, with the field work undertaken by a freelance geologist contracted on a fixed sum.

Based on criteria used to assess potential RIGS in Barnsley and Rotherham, RIGS in Doncaster were selected on the strength of:

- Representing a full cross-section of geological formations in the area
- Scientific value
- Education value
- Accessibility and aesthetic, recreation and amenity value
- Links with other biological, archaeological and architectural interests

Although several active hard rock and sand and gravel quarries were assessed as part of the 1997 field survey work, with some considered to merit RIGS status, the existing planning conditions and legislation, together with commercial interests of quarry operators deemed it necessary to omit certain sites from the RIGS selection process, even though on strict merit these would have been included in the final short list.

The increased protection now afforded to geological sites by PPS9 and the Local Development Framework and the realistic prospect of Geodiversity Action Plans, produced in conjunction with the private sector, has emphasised the need to devote professional expertise to the current project. With more time to assess each of the RIGS and related geological features, the 2007 Survey highlights the opportunity to reinforce geological links with current management plans, especially along the Don Gorge, where there is great potential to link to funding opportunities with English Heritage and Natural England, and along the Permian limestone escarpment.

The resurvey of sites was conducted during mid January to early March 2007. Site assessment data was collected using the UKRIG Site Assessment Form (see Appendix) and entered into the UKRIGS GeoConservation Microsoft Access database. In practice, this database has proved very difficult to use, especially importing and exporting data and the translation into a user friendly report format. These database problems only came to light once the project was well underway, leaving no opportunity to introduce an alternative system.

It is therefore recommended that when undertaking future surveys of Sites of Scientific Interest within the borough, the compatibility of using this database alongside others used in Doncaster for Ecology, Archaeology and Architecture should be taken fully into account.

A summary of the 2007 survey is presented in Table 2 with sites plotted on Figure 13. Of the 28 sites listed in 1997, 23 are recommended for continued designation as RIGS, while five sites are proposed for removal from the list. Six new sites were surveyed and are recommended for designation as RIGS, bringing the total RIGS in Doncaster to 29. For full details of the individual sites see individual site assessment reports in the Appendix.

With respect to geological formations that are not well represented, difficulties still remain in that both the Permian marls and associated minerals, together with the soft Quaternary sediments, are extremely susceptible to natural weathering, quarrying operations and development and these are probably best recorded in addition to an archaeological or ecological survey that may be required as part of future works.

Table 2 Summary of Doncaster RIGS and potential RIG sites (D and DR in site number column respectively)

Site No	Site Name	Site type	NGR	Stratigraphy	Current site condition	Geodiversity value	Score	Add, Remove or Keep
D6	Denaby Lane	Road cutting	SK 489 995	Mexborough Rock, Pennine Middle Coal Measures Formation	Much of the section is overgrown and would be improved by selective clearance	Excellent geodiversity site (to be extended) for geology and a wide variety of landforms and fluvial geomorphology	9	Keep
D166	Doncaster Road	Disused quarry	SK 492 998	Mexborough Rock, Pennine Middle Coal Measures Formation	Partially overgrown	Moderately high, just because it is still the best exposure of Mexborough Rock recorded	7	Keep
D177	Wath Road Railway Cutting	Railway cutting	SE 461 002	Mexborough Rock, Pennine Middle Coal Measures Formation	completely infilled	No geodiversity value as site now completely infilled	0	Remove
DR2	Harlington Railway Cutting	Railway cutting	SE 477 033	Ackworth Rock, Pennine Middle Coal Measures Formation	Most of the eastern end is embankment. Western end more rocky but heavily vegetated	Limited. Very limited exposure of value to research and field mapping only	5	Add
DR3	Cadeby Waste Water Works	Disused quarry	SE 512 004	Dalton Rock, Pennine Upper Coal Measures Formation	Clean, clear rock faces. Shrubs and vegetation to lower rock face	Very good, on strength of rarity of Dalton Rock and possible associations with unconformable Permian rocks	8	Add
DR1	Denaby Woods – Mexborough Oxbow Lake	Geomor. interest site	SK 478 995	Pennine Coal Measures Group	Areas of interest are in good condition but lie in and around areas that are rapidly developing	Very good. Faulting and folding, alluvial processes and geomorphology	9	Add
DR6	Barnburgh Cliff	Exposure	SE 501 037	Dalton Rock, Pennine Upper Coal Measures Formation Wetherby Member, Cadeby Formation	Very good. Plenty of good exposure	A good site to show reef formation and associated beds, fissures and related deposits, an unconformity and geomorphology	9	Add
D11	Hazel Lane Quarry	Active quarry	SE 500 110	Pennine Upper Coal Measures Formation Wetherby Member, Cadeby Formation	Plenty of exposed faces but quarry is being progressively landfilled	Good example of lithological variation in the Cadeby Formation but limited by planning permission and landfill	5	Keep
D4	Watchley Crags	Disused quarry	SE 476 068	Yellow Sands Formation Wetherby Member, Cadeby Formation	The exposures furthest away from Watchley Lane are very good but the nearest are being increasingly littered	A very good site, for the rarity value, lithological variety and historic/industrial archaeological interests	8	Keep
D15	Melton Park	Disused quarry	SE 509 014	Yellow Sands Formation Wetherby Member, Cadeby Formation	The limestone is in excellent condition. The Yellow Sands would benefit considerably from vegetation clearance	A good range of geological processes can be demonstrated. Very high aesthetic/landscape value	8	Keep

Site No	Site Name	Site type	NGR	Stratigraphy	Current site condition	Geodiversity value	Score	Add, Remove or Keep
D133	Hooton Pagnell	Disused quarry	SE 483 074	Wetherby Member, Cadeby Formation	Vegetation and rubbish etc make access awakward but rock faces are largely free of vegetation and well exposed	A very good site, for the rarity value, lithological variety and historic/industrial archaeological interests	8	Keep
D13	North Cliff Quarry	Disused quarry	SK 507 992	Wetherby Member, Cadeby Formation	Requires extensive clearance to improve access to best exposures.	A very good site with variable lithology, excellent landscape value and proximity to several very notable historic buildings	9	Keep
D5	Hooton Pagnell Village Pound	Natural exposure	SE 486 081	Wetherby Member, Cadeby Formation	Very good, but some cutting back of vegetation around the reef exposure is required on a regular basis	Outstanding example of the creation of an estate village using local building materials with a particularly good reef	9	Keep
D20 – D22	Cadeby Cliff – Constitution Hill	Natural exposure	SK 511 999	Wetherby Member, Cadeby Formation Glaciofluvial Deposits	Several natural rock features well exposed. Old quarry requires clearance to facilitate access	A very good geodiversity site with a variety of lithological, geomorphological and historical interests	9	Keep
D112	Parknook Quarry	Active quarry	SE 513 128	Wetherby Member, Cadeby Formation	Commercial use of site and rock waste, rubbish and vegetation etc limit ease of access	Moderate geodiversity value. Some interesting geological features but mainly valuable as a potential source of building stone	7	Keep
D28	Pot Ridings Wood Railway Cutting	Railway cutting	SE 526 003	Wetherby and Sprotbrough Members, Hampole Beds, Cadeby Formation	Good exposures but access along the cutting was difficult at the time of the survey due to deep mud	A very good insight into the importance of geology in determining the route of railway networks	9	Keep
DR5	Levitt Hagg Wood	Disused quarry	SE 538 011	Sprotbrough Member, Cadeby Formation	Overgrown but there are reasonable rock exposures to be seen	Possesses group value with other sites along the Don Gorge	7	Add
D94	Warmsworth Quarry	Active quarry	SE 535 004	Sprotbrough Member, Cadeby Formation	Very good	Unusual occurrence of brecciated dolostone	8	Keep
D78	Warmsworth Park	Disused quarry	SE 544 030	Sprotbrough Member, Cadeby Formation	Very good but needs to be cleaned regularly	A wide range of geological processes can be demonstrated, especially in conjunction with other nearby sites	9	Keep
DR4	Nearcliff Wood Quarries	Disused quarry	SK 527 995	Cadeby Formation	Some rubbish, fires and other debris associated with redundant quarries but acceptable for scientific visits	Extremely important in at least both a regional and national context for the use and exploitation of a natural resource	10	Add
D300	Conisbrough Caves East	Caves	SK 523 992	Cadeby Formation	Some of cave entrances have been covered by landfill	Caves are of specialist speleological interest but associated breccias, rifts and slump structures are very interesting	8	Keep

Site No	Site Name	Site type	NGR	Stratigraphy	Current site condition	Geodiversity value	Score	Add, Remove or Keep
D301	Conisbrough Caves West	Caves	SK 515 996	Cadeby Formation	D/K	Entrances to both caves were not found and no geodiversity value could therefore be assigned	0	Remove
D302	Conisbrough Caves South	Caves	SK 511 985	Cadeby Formation	Full of rubbish and damaged by fire. Well is maintained	Speoleogical research potential. Spring line associated with fault. Historic associations	8	Keep
D303	Levitt Hagg Hole	Caves	SE 538 009	Cadeby Formation	Not found	The grid reference for the cave entrance appears to coincide with the restored Levitt Hagg Landfill Site and was not found	0	Remove
D61	New Edlington Brick Pit	Disused pit	SK 534 986	Edlington Formation Till	Gypsum and calcareous mudstone not visible at time of survey. Till has limited exposures that are susceptible to vegetation growth	Main value relates to rare occurrence of gypsum in a landscape dominated by human activity, waste tips and industry	5	Keep
D31	Leys Hill Bridge	Railway cutting	SE 523 067	Edlington Formation	Largely overgrown and obscured by grass, hawthorns and osiers	Limited value except use as a marker for the position of the Edlington Formation	5	Keep
D51	Hexthorpe Flatts – The Dell	Disused quarry	SE 558 020	Brotherton Formation Till	Very good. Only periodic removal of plant growth from rock faces required	A good introduction to magnesian limestone in situ and various man made features using stone. Landscape/rockery stone for ornamemtal garden features	7	Keep
D87	Brodsworth Quarry	Disused quarry	SE 530 070	Brotherton Formation	Misidentified site	None	0	Remove
D99	Skelbrooke Quarry	Disused quarry	SE 505 114	Brotherton Formation	Landfilled	None	0	Remove
D44	Cedar Road Adventure Playground	Disused quarry	SE 558 010	Nottingham Castle Formation Till and Glaciofluvial deposits	Some clearance of faces and rubbish required. Boundary fences need attention due to undermining /erosion of gravels	Good accessible introduction to a variety of lithologies and associations with quarrying and construction	6	Keep
D101	Dunsville Quarry	Active quarry	SE 655 075	Sherwood Sandstone Group Older River Gravel (River Terrace Deposits)	Exposures noted in the 1997 survey are obliterated but there is potential for further exposure with good management	A good site to demonstrate a wide variety of sedimentary processes	7	Keep
D102	Common Lane Quarry	Disused quarry	SE 567 962	Sherwood Sandstone Group Glaciofluvial deposits	Good condition. Clean and clear quarry faces. Sand and gravel also well exposed.	Remote location but one of few exposures of Sherwood Sandstone not under threat, with Glaciofluvial deposits	7	Keep

Site No	Site Name	Site type	NGR	Stratigraphy	Current site condition	Geodiversity value	Score	Add, Remove or Keep
D190–192	Blaxton Common	Disused quarry	E 685 015	Sherwood Sandstone Group Older River Gravel (River Terrace Deposits)	Sandstone exposures clear and visible but Older River Gravels are increasingly becoming overgrown	Links well with biodiversity interests, but lithologies not easily studied due to access difficulties	7	Keep
D109	Hurst Plantation Quarry	Disused quarry	SK 640 990	Glaciofluvial deposits	Plenty of exposure, but needs improvement of pathways and access to exposures if land is to be properly managed	Limited lithologies and interest, other than sedimentology but a good expossure of Anglian sand and gravel	7	Keep

7 Sources of Information

The following sources of information were used in this project:

7.1 BGS MAPS

1:50 000 scale

E78 Wakefield (S&D) 1998, E78 Wakefield (SwD) 1978
E79 Goole (S&D) 1971, E79 Goole (SwD) 1972
E87 Barnsley (S&D) 1976
E88 Doncaster (S&D) 1969, E88 Doncaster (SwD) 1969
E100 Sheffield (S&D) 1974
E101 East Retford (S&D) 1967

7.2 SOUTH YORKSHIRE RIGS GROUP

Inventory of Regionally Important Geological Sites Doncaster 1997

7.3 DONCASTER COUNCIL

Doncaster Museum Geological Site Inventory (Geosite1.xls)
Doncaster Museum Geological Sites featured in BGS memoir (Geosite2.xls)

7.4 PROJECT GIS

The following files were used in the project GIS:

Dataset	Figure No.	Format	Supplier	Licence for BGS use	Licence fee
Earth science					
Digital Geology (DiGMapGB-50 & 10)	3, 4, 6	ESRI shape file	BGS	No	No
Quaternart domains and lithostratigraphy	5, 7	ESRI shape file	BGS	No	No
BritPits database of mines and quarries	10	ESRI shape file	BGS	No	No
Index of onshore petroleum wells	11	ESRI shape file	BGS	No	No
Wellmaster database of water wells	12	ESRI shape file	BGS	No	No
Geological Conservation Review sites (GCR)	13	Web table	JNCC	No	No
Sites of Special Scientific Interest (SSSI)	8	ESRI shape file	NE	Yes	No
Regionally Important Geological and Geomorphological Sites (RIGS)	13	Excel table	DMBC	No	No
Topography and landscape					
NEXTMap Britain DSM from radar altimetry	9	Raster images	Intermap, but processed by BGS	Yes	Yes
1:250k, 1:50k, 1:25k, 1:10k topography, National Grid, Admin Meridian		Raster and vector	OS	Yes, PGA	Yes
Natural Areas	8	ESRI shape files	NE	Yes	No

Table 3 Digital datasets used in the project GIS.

8 Glossary

Alluvial	Environments, actions and products of rivers or streams.
Anhydrite	Anhydrous calcium sulphate, $CaSO_4$. A white, sometimes greyish, bluish or purple mineral. When exposed to water, anhydrite readily transforms to the more commonly occurring gypsum, ($CaSO_4 \cdot 2H_2O$) by the absorption of water. Anhydrite is commonly associated with calcite, halite, and sulphides such as galena, chalcopyrite, molybdenite, and pyrite in vein deposits.
Armorican	The Gaulish name for the area that includes the Brittany peninsula and the territory between the Seine and Loire rivers, extending inland to an indeterminate point and down the Atlantic coast.
Anticline	An arch-shaped fold in rock in which the rock layers are upwardly convex. The oldest rock layers form the core of the fold, and outward from the core progressively younger rocks occur.
Argillaceous	Detrital sedimentary rocks composed of very fine grain silt or clay-sized particles (<0.0625 mm), usually with a high content of clay minerals.
Bedding	A feature of sedimentary rocks, in which planar or near-planar surfaces known as bedding planes indicate successive depositional surfaces formed as the sediments were laid down.
Bedrock	A term used to describe unweathered rock below soil or superficial deposits. Can also be exposed at the surface.
Bivalve	class of molluscs with paired oval or elongated shell valves joined by a hinge.
Brachiopod	A phylum of solitary marine shelled invertebrates.
Breccia	Coarse-grained clastic sedimentary rock consisting of angular fragments of pre-existing rocks.
Brickclay	Mudstone used in the manufacture of structural clay products such as bricks, pavers, roofing tiles and clay pipes.
Calcite	Calcium Carbonate [$CaCO_3$] a widely distributed mineral and a common constituent of sedimentary rocks, limestone in particular. Also occurs as stalactites and stalagmites and is often the primary constituent of marine shells.
Carboniferous	A geological period [359–299 Ma] preceded by the Devonian and followed by the **Permian**.
Conglomerate	A sedimentary rock, a significant proportion of which is composed of rounded pebbles and boulders, greater than 2mm in diameter, set in a finer-grained groundmass.
Clast	Particle of broken down rock, eroded and deposited in a new setting.
Clastic	Applies to the texture of rocks which are comprised of fragments of pre-existing rocks which have been weathered or eroded.
Cross-bedding	Cross-stratification formed by the migration of dunes and sand waves on a sediment surface.
Cross-lamination	Cross-stratification formed by the migration of ripples on a sediment surface. **Foresets** less than 10 mm thick.
Cross-stratification	A general term for the internal bedding structure produced in sand by moving wind or water. If the individual inclined layers (**foresets**) are thicker than 10 mm the cross-stratification may be referred to as **cross-bedding**. Thinner inclined layering is called **cross-lamination**. Cross-stratification forms beneath ripples

	and dunes. The layering is inclined at an angle to the horizontal, dipping downward in the downcurrent direction.
Cuesta	Asymmetric landform with one face (dip slope) long and gentle and conforming with the dip of the resistant bed or beds that form it, and the opposite face (scarp slope) steep or even cliff like and formed by the outcrop of the resistant rocks. Formed by the differential erosion of gently inclined strata.
Desiccation breccia	A layer of mudstone completely broken by subaerial cracking as it dries out in a terrestrial environment.
Devensian	The last glacial stage in Britain, lasting from around 70 000 BP (Before Present) to about 10,000 BP.
Dinoflagellate	The dinoflagella are a large group of flagellate organisms. Most are marine plankton, but they are also common in fresh water habitats. Their populations are distributed depending on temperature, salinity, or depth. Dinoflagellate cysts are commonly preserved in the fossil record and are useful for stratigraphic correlation and palaeoenvironmental analysis.
Discontinuity	A break in sedimentation.
Dolomite	Calcium magnesium carbonate, A sedimentary rock-forming mineral [$CaMg(CO_3)_2$].
Dolostone	A sedimentary rock usually formed by the dolomitization of limestones.
Dolomitization	Diagenetic conversion of calcium carbonate (limestone) to calcium magnesium carbonate (dolomite).
Eustatic	World-wide changes in sea-level caused either by tectonic movement or growth or melting of glacial ice-sheets (glacioeustatic).
Evaporite	Sedimentary rock formed by the precipitation of salts from natural brines.
Facies	The characteristic features of a rock unit, including rock type, mineralogy, texture and structure, which together reflect a particular sedimentary, igneous or metamorphic environment and/or process.
Fault	A fracture in the Earth's crust across which the rocks have been displaced relative to each other.
Fireclay	Sedimentary mudstones that occur as seatearths underlying almost all coal seams. They represent fossil soils on which the coal-forming vegetation grew. The term was originally derived from their ability to resist heat. They are mainly used in the manfacture of high-quality facing bricks.
Fluvial	Referring to a river environment.
Foraminifera	The Foraminifera, or forams for short, are a large group of amoeboid organisms. They typically produce a shell, or test, which can have either one or multiple chambers. About 275,000 species are recognized, both living and fossil. They are usually less than 1 mm in size and are commonly preserved in the fossil record. Useful for stratigraphic correlation and palaeoenvironmental analysis.
Foreset	The inclined surface within a cross set produced by the forward movement of the slip-face of a ripple or dune.
Glaciofluvial	Refers to sediments deposited by flowing glacial **meltwater.**
Graben	A graben is a structural feature consisting of a depressed block of land bordered by parallel normal faults.
Holocene	The youngest epoch of the Quaternary Period. Covers the last 10 000 years.
Lacustrine	Refers to a lake environment.
Lamellibranchs	Any of the bivalve mollusks of the class Lamellibranchia, including the clams,

	scallops, and oysters. Also called pelecypod.
Lithology	The character of a rock expressed in terms of its mineral composition, structure, grain size and arrangement of its constituents.
Marl	Calcareous (lime-rich) mudstone.
Meltwater	Water produced by melting of snow or ice.
Monocline	A linear of fold in which strata dip in one direction between horizontal or uniformally dipping layers on each side.
Ooid	Sub-spherical, sans-sized carbonate particle that has concentric rings of calcium carbonate surrounded a nucleus of another particle. Ooids usually form on the sea floor, most commonly in shallow tropical seas.
Periglacial	Conditions, processes and landforms associated with cold, nonglacial environments.
Permian	A geological period [299–251 Ma] preceded by the **Carboniferous** and followed by the **Triassic**.
Pisoids	A variety of calcite consisting of aggregated globular concretions about the size of a pea. Pisolites form by the precipitation of calcium carbonate around nuclei trapped in sediment within the vadose zone of soils or marine tidal flats.
Pyrolusite	Pyrolusite is a mineral consisting essentially of manganese dioxide (MnO_2) and is important as an ore of manganese. It is a soft, black, amorphous appearing mineral, often with a granular, fibrous or columnar structure, sometimes forming reniform crusts.
Reef	A rigid, wave-resistant organosedimentary build-up constructed by carbonate organisms. Reefs are held up by a macroscopic skeletal framework.
Rhomb	Equilateral oblique-angled parallelogram shaped mineral grains.
Rip-up clasts	In a fluvial setting, semi-lithified mudstone or siltstone overbank deposits ripped up during times of flooding and re-deposited in the channel.
Saccharoidal	A mineral Composed of tiny, equidimensional crystals that resemble grains of sugar.
Seatearth	A bed of rock underlying a coal seam, representing a fossil soil that supported the vegetation from which the coal was formed.
Sedimentology	The study of sedimentary rocks and of the processes by which they were formed; the description, classification, origin, and interpretation of sediments.
Sedimentary rock	A rock formed in one of three main ways: by the deposition of the weathered remains of other rocks (clastic sedimentary rock); by the deposition of the results of biogenic activity; and by precipitation from solution. Four basic processes are involved in the formation of a clastic sedimentary rock: weathering (erosion), transportation, deposition and compaction.
Solifluction	Solifluction is a slow downslope flow of water-saturated fragmental material or soil. It is promoted by the existence of permafrost which traps snow and ice melt within the surface layer making it more fluid.
Stylolites	Stylolites are irregular surfaces that commonly appear as dark, jagged lines on exposed surfaces of carbonate rock (and rarely on other sedimentary rock types). Their origin is usually attributed to solution that occurs after the host rock was formed. The dark layers are insoluble residues.
Strata	Rocks that form layers or beds.
Stratigraphy	The definition and description of the stratified rocks of the Earth's crust.

Subaerial	Located or occurring on or near the surface of the earth.
Syncline	A basin- or trough-shaped fold in rock in which rock layers are downwardly concave. The youngest rock layers form the core of the fold and outward from the core progressively older rocks occur.
Triassic	A geological period [251–200 Ma] preceded by the **Permian** and followed by the Jurassic.
Unconformable	A term generally applied to younger strata that do not conform in position or that do not have the same dip and strike as those of the immediately underlying rocks. Also applies to the contact between unconformable rocks.
Unconformity	A surface of contact between two groups of **unconformable** strata. Represents a break in the geological record where a combination of erosion and lack of deposition was taking place.
Vug	Vugs are small cavities inside rock that are formed when crystals form inside a rock matrix and are later removed through erosive processes, leaving behind voids. A common cause of vugs is minerals precipitating from solution in water, and then later being dissolved again by less saturated water. The inner surfaces of vugs are often coated with some of the mineral matter that formed them. Fine crystals are often found in vugs where the open space allows the free development of external crystal form.

9 Selected Bibliography

9.1 GENERAL GEODIVERSITY

ENGERING, S & BARRON, H F. 2005. Doncaster Geodiversity Assessment. *British Geological Survey Commissioned Report*, CR/07/025N.

BUREK, C. 2005. A tale of two sites: how RIGS can complement SSSIs. *Earth Heritage*, Issue 24, 24–25.

BUREK, C. 2006. Do we need a National GAP? *Earth Heritage*, Issue 25, 10.

BENN, D I and EVANS, D J A. 1988. *Glaciers and Glaciation.* Arnold, London. ISBN 0 340 58431 9

BENNET, M R and DOYLE, P. 1996. The rationale for earth heritage conservation and the role of urban geology. 3–10 in *Geology on Your Doorstep*. BENNET, M R, DOYLE, P., LARWOOD, JG and PROSSER, C D. (Editors). (London: Geological Society.)

BENNET, M R, DOYLE, P, GLASSER, N F, and LARWOOD, J G. 1997. Geological conservation in disused quarries: how effective is the conservation void? *Journal of Environmental management*, Vol. 50, 223–233.

BOULTON, G S, JONES, A S, CLAYTON, K M and KENNING, M J. 1977. A British ice sheet model and patterns of glacial erosion and deposition in Britain. 231–246 in *British Quaternary studies: recent advances.* SHOTTON, F W. (editor). (Oxford: Oxford University Press.) ISBN 0 198544146

DAMIGOS, D, and KALIAMPAKOS, D. 2003. Assessing the benefits of reclaiming urban quarries: a CVM analysis. *Landscape and UrbanPlanning*, Vol. 64 Pt. 4, 249–258.

DENLEY, A, and PROSSER, C D. 2001. Working together – business and nature conservation: turning words into action. *Quarry Manager*, Vol. 28, 35–38.

DOYLE, P and BENNET, M R. 2000. Earth heritage conservation: the importance of the built environment. *Urban Design Studies* Vol. 5, 47–56.

DOYLE, P and BENNET, M R. 1998. Earth heritage conservation: the past, present and future agenda? 43–67 in *Issues in Environmental Geology*. BENNET, M R. and DOYLE, P. (Editors). (London: Geological Society.)

DOYLE, P, BENNET, M R and ROBINSON, E. 1996. 1996. Creating urban geology: a record of Victorian innovation in park design.78–84 in *Geology on Your Doorstep*. BENNET, M R, DOYLE, P., LARWOOD, J G and PROSSER, C D. (Editors). (London: Geological Society.)

ENGLISH NATURE. 1996. Earth heritage conservation in England: A Natural Areas perspective. *English Nature Research Report*, No. 158. ISSN 0967-876X

ENGLISH NATURE. 2004. *Geology and biodiversity – making the links* (Peterborough: English Nature.) ISBN 1 85716 803 8

ENGLISH NATURE. 2004. *The conservation of soft sediments on geological SSSIs*. (Peterborough: English Nature.) ISBN 1 85716 802X

ENGLISH NATURE. 2004 Local Geodiversity Action Plans: setting the context for geological conservation, *English Nature Research Report*, No. 560. ISSN 0967-876X

ENGLISH NATURE. 2004. Geological conservation benefits for biodiversity. *English Nature Research Reports,* No. 561. ISSN 0967-876X

ENGLISH NATURE. 2004. Linking Geology and Biodiversity. *English Nature Research Reports,* No. 562. ISSN 0976 876X

ENGLISH NATURE. 2004. The conservation and management of unconsolidated geological sections. *English Nature Research Reports,* No. 563. ISSN 0976 876X

ENGLISH NATURE. 2004. Local Geodiversity Action Plans – sharing good practice workshop, Peterborough, 3 December 2003. *English Nature Research Report*, No. 601. ISSN 0967-876X

ENGLISH NATURE. 2006. The social and economic value of the UK's geodiversity. *English Nature Research Reports,* No. 709. ISSN 0967 876X

ENGLISH NATURE. 2006. G*eological conservation: a guide to good practice*. (Peterborough: English Nature.) ISBN 1 85716 9060 9

ENGLISH NATURE, QUARRY PRODUCTS ASSOCIATION and SILICA AND MOULDING SANDS ASSOCIATION. 2003. *Geodiversity and the minerals industry: Conserving our geological heritage*. (Entec UK Ltd.) ISBN 0 9535400 3 0

ELLIS, N V, BOWEN, D Q, CAMPBELL, S, KNILL, J L, MCKIRDY, A P, PROSSER, C D , VINCENT, M A, and WILSON, R C L. (1996) *An introduction to the Geological Conservation Review*. Geological Conservation Review Series No 1, (Peterborough: Joint Nature Conservation Committee.) ISBN 1861074034

GORDON, J E, and LEYS, K F. 2001. Earth science and the natural heritage: developing a more holistic approach. 5–18 in *Earth science and the natural heritage: interactions and integrated management.* GORDON, J E, and LEYS, K F, (editors). (Edinburgh: The Stationery Office.) ISBN 0 11 497283 4

GORDON, J E, and MACFAYDEN, C C J. 2001. Earth science conservation in Scotland: state, pressures and issues. 130–147 in *Earth science and the natural heritage: interactions and integrated management.* GORDON, J E, and LEYS, K F, (editors). (Edinburgh: The Stationery Office.) ISBN 0 11 497283 4

GRAY, J M. 2002. Landraising of waste in England, 1900-2000: a survey of the geomorphological issues raised by planning applications. *Applied Geography*, Vol. 22, 209–234.

GRAY, M. 2004. *Geodiversity: valuing and conserving abiotic nature*. (Chichester: John Wiley & Sons.) ISBN 0 470 84896 0

GRAY, M. 2005. What's in a name? Geotope and Geodiversity? *Earth Heritage*, Issue 23, 6.

GRAY, M. 2005. Planning for geoconservation. *Earth Heritage*, Issue 23, 16–17.

INGHAM, S M, DOYLE, P and BENNET, M R. 1996. The changing nature of the urban earth heritage site resource. 31–35 3–10 in *Geology on Your Doorstep*. BENNET, M R, DOYLE, P, LARWOOD, JG and PROSSER, C D. (Editors). (London: Geological Society.)

LARWOOD, J. 2004. How to mind the LGAP. *Earth Heritage*, Issue 22, 6.

LARWOOD, J. 2006. LGAPS: where are we now? *Earth Heritage*, Issue 25, 9.

LARWOOD, J and DURHAM, E. 2005. *Involving people in geodiversity* (Peterborough: Joint Nature Conservation Committee.)

LAWRENCE, D J D, VYE, C L, YOUNG, B. 2004. *Durham Geodiversity Audit.* (Durham: Durham County Council.) ISBN 0 902178 21 0

LOWE, J J, and WALKER, M J C. 1997. *Reconstructing Quaternary Environments (2nd Edition).* (Harlow: Prentice Hall.) ISBN 0582101662

MALTBY, E, and PROCTOR, M. 1996. Peatlands: their nature and role in the biosphere. 11-19 in *Global Peat Resources*. LAPPALAINEN, E. (Editor). (Jyska (Finland): International Peat Society.)

NATURE CONSERVANCY COUNCIL. 1990. *Earth science conservation in Great Britain: A strategy. (*Peterborough: Nature Conservancy Council.) ISBN 0861396898

NICHOLAS, C. 2004. *Geodiversity audit of active aggregate quarries: quarries in Devon*. Exeter: David Roche GeoConsulting. Available from: www.devon.gov.uk/text/overview_report_whole.pdf [Accessed 232March 2007].

NORTH PENNINES AONB PARTNERSHIP. 2004. *North Pennines Area of Outstanding Natural Beauty: A Geodiversity Audit and Action Plan 2004–2009.*

OFFICE OF THE DEPUTY PRIME MINISTER. 2005. *Planning Policy Statement 9: Biodiversity and Geological Conservation.* (London: HMSO.) ISBN 0 11 75394 6

OWEN, D, PRICE, W, and REID, C. 2005. *Gloucestershire Cotswolds: Geodiversity Audit & Local Geodiversity Action Plan*. (Gloucester: Gloucestershire Geoconservation Trust.) ISBN 1 904530 07 9

BENTON, M J, and SPENCER, P S. 1995. Fossil reptiles of Great Britain. Geological Conservation Review Series No. 10. Joint Nature Conservation Committee. 386 pages. (London: Chapman and Hall.) ISBN 0 41262 040 5

PARKES, M. 2006. Geological heritage in the Emerald Isle. *Earth Heritage,* Issue 25, 20–22.

PROSSER, C. 2005. New Planning Policy Statement leaves scope for more emphasis on geology. *Earth Heritage,* Issue 23, 17–18.

PROSSER, C. 2006. Massive step for geological conservation. *Earth Heritage,* Issue 25, 8–9.

PROSSER, C. 2007. Meshing up our heritage. *Earth Heritage,* Issue 27, 10–12.

PROSSER, C, MURPHY, M, and LARWOOD, J. 2006. *Geological Conservation:a guide to good practice. English Nature* 8–9. ISBN 1 85716 906 9

ROYAL SOCIETY FOR NATURE CONSERVATION. 1999. RIGS Handbook [online]. Last update 2000 [cited 20 March 2006]. Available from http://www.ukrigs.org.uk/html/ukrigs.php?page=hbcontent&menu=promo

SCOTT, P W, SHAIL, R, NICHOLAS, C and ROCHE, D. 2007. *The Geodiversity Profile Handbook.*(Exeter: David Roche GeoConsulting.)

SCOTT, P W, NICHOLAS, C, TURNER, H, ROCHE, D and SHAIL, R. 2007. *Access and safety at geological sites: A manual for landowners, quarry operators and the geological visitor*. (Exeter: David Roche GeoConsulting.)

STACE, H, and LARWOOD, J G. 2006. *Natural foundations: geodiversity for people, places and nature*. Peterborough: English Nature. ISBN 1 85716 900 X

STANLEY, M. 2001. Welcome to the 21st century. *Geodiversity Update.* No. 1 p. 1.

STUART,M E, WHITEHEAD, E J and MORRIS, B L. 2004. AISUWRS Work-package 4: Water quality of the Doncaster aquifer. *British GeologicalSurvey Commissioned Report*, CR/04/026N. 40pp.

USHER, M B. 2001. Earth Science and the natural heritage: a synthesis. 314–324 in *Earth science and the natural heritage: interactions and integrated management.* GORDON, J E, and LEYS, K F, (editors). (Edinburgh: The Stationery Office.) ISBN 0 11 497283 4

VINCENT, P. 2004. What's in a name? Geotope or Geodiversity? *Earth Heritage,* Issue 23, 7.

WETHERELL, A. 2004. Linking geology and biodiversity. *Earth Heritage,* Issue 23, 20–21.

WILSON, R C L, DRURY, S A, and CHAPMAN, J L. 2000. *The Great Ice Age*. (London: Routledge.) ISBN 0 415 19841 0

WOODLEY-STEWART, C, and YOUNG, B. 2004. Geodiversity takes its rightful place. *Earth Heritage,* Issue 23, 10–11.

9.2 GEOLOGY OF DONCASTER

ALLEN, D J, BREWERTON, L J, COLEBY, L M, GIBBS, BR, LEWIS, M A, MACDONALD, A M, WAGSTAFF, S J, and WILLIAMS, A T. 1997. The physical properties of major aquifers in England and Wales. *British Geological Survey Technical Report* WD/97/34, 312pp. Environment Agency R&D Publication 8.

BATEMAN, M D, BUCKLAND, P C. 2001. Non Glacial and Post Glacial History. 13–19, in *The Quaternary of East Yorkshire and North Lincolnshire*. BATEMAN, M D, BUCKLAND, P C, FREDERICK, C D and WHITEHOUSE, N J (editors). Quaternary Research Association Field Guide.

BATEMAN, M D., BUCKLAND, P C, CARPENTER, R, DAVIES, S, FREDERICK, C D. GEAREY, B, MURTON, J. B, and WHITEHOUSE, N J. 2001. Cove Farm Quarry, Westwoodside (SK 737008). 141–160 in *The Quaternary of East Yorkshire and North Lincolnshire*. BATEMAN, M D, BUCKLAND, P C, FREDERICK, C D and WHITEHOUSE, N J (editors). Quaternary Research Association Field Guide.

BOSWIJK, G. 2003. The buried forest of Thorne Moors. *Thorne and Hatfield Moors Papers,* Vol. 6, 52–65.

BOSWIJK, G and WHITEHOUSE, N J. 2002. *Pinus* and *Prostomis*, a dendrochronological and palaeoentomological study of a mid-Holocene woodland in eastern England. *The Holocene,* Vol. 12, 585–596.

BOSWIJK, G, WHITEHOUSE, N J, SMITH, B and BUCKLAND, P C. 2001. Thorne Moors (SE 7316). 169–177 in *The Quaternary of East Yorkshire and North Lincolnshire*. BATEMAN, M D, BUCKLAND, P C, FREDERICK, C D and WHITEHOUSE, N J (editors). Quaternary Research Association Field Guide.

BRAMLEY, D. 1973. in *The Quaternary of East Yorkshire and North Lincolnshire*. BATEMAN, M D, BUCKLAND, P C, FREDERICK, C D and WHITEHOUSE, N J (editors). Quaternary Research Association Field Guide. Balby Brick Pit, Doncaster, The end of an era. *South Yorkshire studies in Archaeology and Natural History*, Doncaster Museum, 19–23.

BROWN, I T and ROOT. 2001 The Sherwood Sandstone aquifer of the Doncaster and Selby areas. Hydrogeological review. P-S-303.

BUCKLAND, P C. 1979. Thorne Moors, a palaeoentomological study of a Bronze Age site. *Department of Geography, University of Birmingham, Occasional Publication* No. 8. Birmingham.

BUCKLAND, P C. 2001. West Moor, Armthorpe. 99–102 in *The Quaternary of East Yorkshire and North Lincolnshire*. BATEMAN, M D, BUCKLAND, P C, FREDERICK, C D and WHITEHOUSE, N J (editors). Quaternary Research Association Field Guide.

BUCKLAND, P C. 2001. Thorne, Bradholme and Tudworth (SE690133, 694144, 691109). 165–166 in *The Quaternary of East Yorkshire and North Lincolnshire*. BATEMAN, M D, BUCKLAND, P C, FREDERICK, C D and WHITEHOUSE, N J (editors). Quaternary Research Association Field Guide.

BUCKLAND, P C. 2002. Conservation and the Holocene record. An invertebrate view from Yorkshire. *Proceedings of the YNU Conference on the Humber, Supplement to the YNU Bulletin*, Vol. 37, 23–40.

BUCKLAND, P C and DOLBY, M J. 1973. Mesolithic and later material from Misterton Carr, Notts. An interim report. *Transactions of the Thoroton Society, Nottinghamshire*, Vol. **77**, 5–33.

BUCKLAND, P C. and DINNIN, M H. 1997. The rise and fall of a wetland habitat, recent palaeoecological research on Thorne and Hatfield Moors. *Thorne and Hatfield Moors Papers,* Vol. 4, 1–18.

BUCKLAND, P C and KENWARD, H K. 1973. Thorne Moor, a palaeoecological study of a Bronze Age site. *Nature,* Vol. 241, 405–406.

BUCKLAND, P C and SADLER, J P. 1985. Late Flandrian alleviation in the Humberhead Levels. *East Midland Geographer,* Vol. 8, 239–251.

BUCKLAND , P C. and SMITH, B. 2003. Equifinality, conservation and the origins of lowland raised mires. The case of Thorne and Hatfield Moors. *Thorne and Hatfield Moors Paper*s, *Vol.* 6, 30–51.

CARROLL, D M. HARTNUP, R. and JARVIS, R A. 1979. Soils of South and West Yorkshire. Soil Survey of England and Wales, Harpenden.

CARTER, Rev. W. L. 1905. Boulder clay at Balby. *Proceedings of the Yorkshire Geological Society*, Vol. 15, 417.

CLAYTON, A R. 1979. The sand and gravel resources of the country around Bawtry, South Yorkshire: description of 1:25 000 resource sheet SK69. *Mineral Assessment Report Institute Geological Sciences,* No. 37.

CORBETT, H H. and KENDALL, P F. 1896. Balby In, Tate, T. (ed.) The Yorkshire Boulder Committee and its tenth year's work. *The Naturalist, Vol.* 22, 59–74.

CORBETT, H H. 1898. 353–356 in The Yorkshire boulder committee and its eleventh year's work, 1896–97. Howarth, J H. (editor). *The Naturalist, Vol.* 23.

CORBETT, H H. 1903. Glacial geology of the neighbourhood of Doncaster. *The Naturalist, Vol.* 28, 47–50.

CORBETT, H H. 1906. Pleistocene mammalian remains near Doncaster. *The Naturalist, Vol.* 31, 109.

CORBETT, H H. 1907. Remains of *Bos primigenius* near Doncaster. *The Naturalist, Vol.* 32, 133.

CULPIN, H. 1905. A post-Permian fault at Cusworth. *Proceedings of the Yorkshire Geological Society,* Vol. 15, 453.

CULPIN, H. 1906. Recent exposures of glacial drift at Doncaster and Tickhill. *The Naturalist,* Vol. 31, 325–327.

CULPIN, H. 1906. Geological notes of Askern. *The Naturalist,* Vol. 31, 369–370.

CULPIN, H. 1907. Geology of Thorne. *The Naturalist,* Vol. 32, 317–318.

CULPIN, H. 1908. Marine beds in the coal measures near Doncaster. *The Naturalist,* Vol. 33, 39–40 and169.

CULPIN, H. 1909. Marine and other fossils in the Yorkshire coal measures above the Barnsley Seam. *Proceedings of the Yorkshire Geological Society*, Vol. 16, 321–334.

CULPIN, H. 1909. Permian fossils in the Doncaster district. *The Naturalist,* Vol. 34, 279–280.

CULPIN, H. 1910. Marine bands in the Yorkshire measures. *The Naturalist*, Vol. 35, 375–375 and Plate XVI.

CULPIN, H and GRACE, G. 1905. Preliminary note on Upper Coal Measures in Yorkshire. *Proceedings of the Yorkshire Geological Society,* Vol. 15, No. 2, 330.

CULPIN, H and GRACE, G. 1905. An exposure of upper coal measures near Conisborough. *The Naturalist,* Vol. 30, 40.

DINNIN, M H and WELSH, M. 2001. Starr Carr (SE 744016). 161–164 in *The Quaternary of East Yorkshire and North Lincolnshire*. BATEMAN, M D, BUCKLAND, P C, FREDERICK, C D and WHITEHOUSE, N J (editors). Quaternary Research Association Field Guide.

EASTERFIELD, T H. 1883. A glacial deposit near Doncaster. *Proceedings of the Yorkshire Geological and Polytechnic Society, Vol.* 8, 212–213.

EDWARDS, W. 1933. A Pleistocene strandline in the Vale of York. *Proceedings of the Yorkshire Geological Society, Vol.* 23, 103–118.

ENVIRONMENT AGENCY. 2001. Water resources for the future: Summary of the Strategy for Midlands Region. http://www.environment-agency.gov.uk/commondata/acrobat/wr_midlands.pdf

ENVIRONMENT AGENCY. 2001. Water resources for the future: Summary of the Strategy for North East Region. http://www.environment-agency.gov.uk/commondata/acrobat/wr_ne.pdf

GAUNT, G D. 1975. The artificial nature of the River Don north of Thorne, Yorkshire. *Yorkshire Archaeological Journal,* Vol. 47, 15–21.

GAUNT, G D. 1976. The Devensian maximum ice limit in the Vale of York. *Proceedings of the Yorkshire Geological Society,* Vol. 40, 631–637.

GAUNT, G D. 1987. The geology and landscape development of the region around Thorne Moors. *Thorne Moors Papers, Vol.* 1, 6–30.

GAUNT, G, BUCKLAND, P and BATEMAN, M. 2006. The geological background to the development and demise of a wetland – the Quaternary history of the Humberhead Levels. *Proceedings of the YNU Conference on the Humberhead Levels, Supplement to the YNU Bulletin,* Vol. 45, 7–46.

GAUNT, G D, COOPE, G R., OSBORNNE, P J. and FRANKS, J W. 1972. An interglacial deposit near Austerfield, southern Yorkshire. *Report of the Institute of Geological Sciences,* No. 72/4.

GAUNT, G D. and GIRLING, M. 1997. Southerly derived glaciofluvial deposits near Scrooby, Nottinghamshire, UK, containing coleopteran assemblage. 125–128 in *Studies in Quaternary Entomology – An Inordinate Fondness for Insects.* AINSWORTH, A C, BUCKLAND, P. C. and SADDLER, J. P. (editors) Quarterly Proceedings, Vol. 5.

GAUNT, G D, GODWIN, C G, SMITH, E G, HARRIS, P M, CORNWELL, J D, CLARKE, M C G, KIRBY, G A, SWALLOW, P W, CALVER, M A, MITCHELL, M, and OWENS, B. 1994. Geology of the country around Goole, Doncaster and the Isle of Axholme: *Memoir of the British Geological Survey*, Sheets 79 and 88 (England and Wales).

GILLIGAN, A. 1918. The Lower Permian at Ashfield brick and Tile Works, Conisbrough. *Proceedings of the Yorkshire Geological Society,* Vol. 19, 289.

GOODDY D C, STUART M E, LAPWORTH D J, CHILTON P J, BISHOP S, CACHANDT G, KNAPP M and PEARSON, T.. 2005. Pesticide pollution of the Triassic Sandstone aquifer of South Yorkshire. *Quarterly Journal of Engineering Geology and Hydrogeology,* Vol. 38, No. 1, 53–63.

GOOSENS, R F, SMITH, E G. and CALVER, M A. 1974. Westphalian. 87–108 in *The Geology and Mineral Resources of Yorkshire*. RAYNER, D H and HEMMINGWAY, J E. (editors). (Leeds:Yorkshire Geological Society.)

GRACE, G. 1906. Notes on sections in gravels near Doncaster. *The Naturalist*, Vol. 31, 184–186.

HARTNUP, R. 1977. Soils of Yorkshire I, Sheet SK 59 (Maltby). *Soil Survey Record* No. 42, Harpenden.

HARWOOD, G M. 1986. The diagenetic history of Cadeby Formation carbonate (EZ1 Ca), Upper Permian, eastern England. 75–86 in *The English Zechstein and related topics*. HARWOOD, G M. and SMITH, D B. (editors). Geological Society, London, Special Publication, No. 22. (London: Blackwell Scientific Publications.) ISBN 0-632-01067-3.

HARWOOD, G M. and SMITH, F. W. 1986. Mineralisation in Upper Permian carbonates at outcrop in eastern England. 103–111 in *The English Zechstein and related topics*. HARWOOD, G M. and SMITH, D B. (editors). Geological Society, London, Special Publication, No. 22. (London: Blackwell Scientific Publications.) ISBN 0-632-01067-3.

HARWOOD, G, SMITH, D B, PATTISON, J and PETTIGREW, T. 1982. Field Excursion Guide EZ 82. *Symposium of the English Zechstein, University of Leeds*.

HEMMINGWAY, J E. 1940. Recent exposures of the Lower magnesian Limestone at Hampole. *Transactions of the Leeds Geological Association,* Vol. **5**, No. 5, 322.

HOWARD, A J. 2001. The Regional Fluvial record. 21–24 in *The Quaternary of East Yorkshire and North Lincolnshire*. BATEMAN, M D, BUCKLAND, P C, FREDERICK, C D and WHITEHOUSE, N J (editors). Quaternary Research Association Field Guide.

HOWARTH, J. H. 1908. The ice boulders of Yorkshire. *The Naturalist* **33**, 219 & 221.

HOWES, C A. 2006. Quaternary mammal remains from the Don Gorge, Doncaster. *Proceedings of the YNU Conference on the Humberhead Levels, Supplement to the YNU Bulletin,* Vol. 45, 46–48.

HOWES, C A and ALLEN, D. 2006. The Branton Oak, and some other ancient oaks of the Hatfield Chase. *Proceedings of the Conference on The Biodiversity of the Humberhead Levels. Supplement to Yorkshire Naturalists' Union Bulletin, Vol.* 45, 70–74.

JARVIS, R A. 1973. Soils of Yorkshire II, Sheet SE 60 (Armthorpe). *Soil Survey Record*, Harpenden.

JENKINSON, R D S. 1978. Archaeological caves and rock shelters in the Creswell Crags area. *Creswell Crags Visitor Centre Research report No. 1*. Nottinghamshire County Council.

JENKINSON, R D S. 1984. *Creswell Crags, Late Pleistocene Sites in the East Midlands.* British Archaeological Reports, British Series 122, Oxford.

JENKINSON, R D , BRAMWELL, D, BRIGGS, D J, GILBERTSON, D D, STEBBINGS, R E, WATTS, C J and WILKINSON, M. 1982. *Death of a Wolf.* Creswell Crags Visitor Centre, Research Report No. 3.

JENKINSON, R D S and GILBERTSON, D D. 1984. *In the Shadow of Extinction, A Late Quaternary Archaeology and Palaeoecology of the Lake, Fissures and Smaller Caves at Creswell Crags SSSI.* Department of Prehistory and Archaeology, University of Sheffield, Sheffield.

JONES, H K, MORRIS, B L, CHENEY, C S, BREWERTON, L J, MERRIN, P D, LEWIS, M A, MACDONALD, A M, COLEBY, L M, TALBOT, J C, MCKENZIE, A A, BIRD, M J, CUNNINGHAM, J and ROBINSON, V K. 2000. The physical properties of minor aquifers in England and Wales. *British Geological Survey Technical Report* WD/00/004, 234pp.

JONES, J E. 1988. Hatfield Moors – case history of a small onshore gasfield. *Petroleum Review, Vol.* 42, (496), 33–37.

JONES, P. 1995. Two early Roman canals? The origins of Turnbrig dike and Bycarrsdike. *Journal of the Railway and Canal Historical Society,* Vol. 31, No. 10, 522–531.

KALDI, J. 1986. Sedimentology of sandwaves in an oolite shoal complex in the Sprotbrough Member of the Cadeby (Magnesian Limestone) Formation (Upper Permian) of eastern England. 63–74 in *The English Zechstein and related topics*. HARWOOD, G M. and SMITH, D B. (editors). Geological Society, London, Special Publication, No. 22. (London: Blackwell Scientific Publications.) ISBN 0-632-01067-3.

KALDI, J. 1986. Diagenesis of nearshore carbonate rocks in the Sprotbrough Member of the Cadeby (Magnesian Limestone) Formation (Upper Permian) of eastern England. 87–102 in *The English Zechstein and related topics*. HARWOOD, G M. and SMITH, D B. (editors). Geological Society, London, Special Publication, No. 22. (London: Blackwell Scientific Publications.) ISBN 0-632-01067-3.

KENDALL, P F and WROOT, H E. 1924. *The Geology of Yorkshire*. (Leeds: James Miles.)

KIRBY, J K. 1861. On the Permian rocks of South Yorkshire and on their palaeontological relations. *Quarterly Journal of the Geological Society,* Vol. 16, 1.

KIRBY, J R. 2001. Regional Late-Quaternary Marine and Perimarine Records. 25–34 in *The Quaternary of East Yorkshire and North Lincolnshire*. BATEMAN, M D, BUCKLAND, P C, FREDERICK, C D and WHITEHOUSE, N J (editors). Quaternary Research Association Field Guide.

LILLIE, M. 1998. Alluvium and warping in the Lower Trent Valley. 103–122 in *Wetland Heritage of the Ancholme and Lower Trent Valleys.* VAN DE NOORT, R. and ELLIS, S. (editors) Humber Wetland Project.

LILLIE, M. 2001. Holocene Human-landscape Interactions. 47–51 in *The Quaternary of East Yorkshire and North Lincolnshire*. BATEMAN, M D, BUCKLAND, P C, FREDERICK, C D and WHITEHOUSE, N J (editors). Quaternary Research Association Field Guide.

MCEVOY, F M, MINCHIN, D, HARRISON, D J, CAMERON, D G, BURKE, H F, SPENCER, N A, EVANS, D J, LOTT, G K, HOBBS, S F, and HIGHLEY, D E. 2006. Mineral Resource Information in Support of National, Regional and Local Planning: South Yorkshire (comprising Metropolitan Boroughs of Barnsley, Doncaster and Rotherham and City of Sheffield). *British Geological Survey Commissioned Report*, CR/04/173N.

MELLARS, P A. 1973. An Upper Palaeolithic site in Edlington Wood. Edlington, an assessment of its recent history, archaeology, geology, natural history and educational value. PHILLIPS, H. (editor) Doncaster Rural District Council, Doncaster.

MITCHELL, G H. 1932. Notes on the Permian rocks of the Doncaster district. *Proceedings of the Yorkshire Geological Society,* Vol. 22, 133–141.

MITCHELL, G H, STEPHENS, J V, BROMHEAD, C E N and WRAY, D A. 1947. Geology of the country around Barnsley. *Memoir of the Geological Survey of Great Britain*, Sheet 87 (England and Wales).

MOSS, M. 1985. Geology in the Doncaster Scientific Society. *The Doncaster Naturalist, Vol.* 1, No. 6, 156–164.

PRICE, D and BEST, D P. 1982. The sand and gravel resources of the country around Armthorpe, South Yorkshire. Description of 1:25 000 resource sheet SE60. *Mineral Assessment Report Institute Geological Sciences,* No. 92.

RAYNER, D H and HEMMINGWAY, J E. (editors.) 1974. *The Geology and Mineral Resources of Yorkshire*. (Leeds:Yorkshire Geological Society.)

RILEY, D N. 1980. *Early landscape from the air*. University of Sheffield, Sheffield.

ROPER, T. 1996. Fossil insect evidence for the development of raised mire at Thorne Moors, near Doncaster. *Biodiversity and Conservation, Vol.* 5, 503–521.

SAMSON, C. and JENKINSON, R D S. 1976. *On the Discovery and Geophysical Survey of New Archaeological Caves in Creswell Crags*. Nottinghamshire and Derbyshire County Council. Creswell Crags Research Report No. 2.

SCHWEITZER, H-J. 1986. The land flora of the English and German Zechstein sequences. 31–54 in *The English Zechstein and related topics*. HARWOOD, G M. and SMITH, D B. (editors). Geological Society, London, Special Publication, No. 22. (London: Blackwell Scientific Publications.) ISBN 0-632-01067-3.

SKIDMORE, P. 1971. The insect fauna of a Bog Oak found near Askern. *The Naturalist,* Vol. 96*,* 111–112.

SKIDMORE, P. 2006. An Inventory of the Invertebrates of Thorne and Hatfield Moors. *Thorne and Hatfield Moors Monographs No. 2*. Thorne and Hatfield Moors Conservation Forum, Thorne.

SMEDLEY, P L, and BREWERTON, L J. 1997. The natural (baseline) quality of groundwaters in England and Wales. Part 2. The Triassic Sherwood Sandstone of the East Midlands and South Yorkshire. *British Geological Survey Technical Report*, WD/97/52.

SMEDLEY, P L, SHAND, P, and EDMUNDS, W M. 1993. Hydrogeochemistry of the Sherwood Sandstone aquifer of the Doncaster area. *British Geological Survey Technical Report*, WD/93/41R.

SMITH, B M. 2002. A palaeoecological study of raised mires in the Humberhead Levels. British Archaeological Reports British Series 336. Oxford, Thorne and Hatfield Moors Monograph No. 1.

SMITH, D B. 1968. The Hampole Beds – a significant marker in the Lower Magnesian Limestone of Yorkshire and Nottinghamshire. *Proceedings of the Yorkshire Geological Society,* Vol. **36**, 463–474.

SMITH, D B. 1995.Marine Permina of England. Geological Conservation Review Series No. 8. Joint Nature Conservation Committee. 205 pages (London: Chapman and Hall.) ISBN 0 41261 080 9

SMITH, D B, HARWOOD, G M, PATTERSON, J and PETTIGREW, T H. 1986. A revised nomenclature for Upper Permian strata in eastern England. 9–17 in *The English Zechstein and related topics*. HARWOOD, G M. and SMITH, D B. (editors). Geological Society, London, Special Publication, No. 22. (London: Blackwell Scientific Publications.) ISBN 0-632-01067-3.

SMITH, R. 2004. *Enjoying the Humberhead Levels*. Halsgrove, Tiverton.

SMITH, W C. 1963. Description of igneous rocks represented among pebbles from the Bunter

Pebble Beds of the Midlands of England. *Bulletin of the British Museum (Natural History) Mineralogy, Vol.* 2, No.1.

Doncaster Chronicle. 1896. Glacial deposits at Balby. March 1896.

STRAW, A. 2002. The late Devensian ice limit in the Humberhead area – a reappraisal. *Quaternary Newsletter, Vol.* 97, 1–10.

STUART M E, WHITEHEAD E J and MORRIS B L. 2004. AISUWRS Work-package 4: Water quality of the Doncaster aquifer. *British Geological Survey Commissioned Report*,CR/04/026N. 40pp.

THOMAS, D and PRICE, D. 1979. The sand and gravel resources of the country around Misterton, Nottinghamshire: description of 1:25 000 resource sheet SK 79. *Mineral Assessment Report Institute Geological Sciences, No. 43.*

TWEDDLE, J C. 2001. Regional Vegetational History. 35–46 in *The Quaternary of East Yorkshire and North Lincolnshire*. BATEMAN, M D, BUCKLAND, P C, FREDERICK, C D and WHITEHOUSE, N J (editors). Quaternary Research Association Field Guide.

VAN DE NOORT, R and ELLIS, S. (editors) 1997. *Wetland Heritage of the Humberhead Levels.* Humberland Wetland Project, Hull.

VAN DE NOORT, R. and ELLIS, S. (editors) 1999. *Wetland Heritage of the Vale of York.* Humberland Wetland Project, Hull.

WARRINGTON, G, AUDLEY-CHARLES, M G, ELLIOTT, R E, EVANS, W B, IVIMEY-COOK, H C, KENT, P, ROBINSON, P L, SHOTTON, F W and TAYLOR, F M. 1980. A correlation of the Triassic rocks in the British Isle. *Special Report of the Geological Society of London*, No. 13.

WHITEHOUSE, N J. 1997. Silent witnesses, an Urwald fossil insect assemblage from Thorne Moors. *Thorne and Hatfield Moors Papers,* Vol. 4, 19–54.

WHITEHOUSE, N J, BOSWIJK, G and BUCKLAND, P C. 2001. The Humberhead peatlands, Thorne and Hatfield Moors. 167–168 in *The Quaternary of East Yorkshire and North Lincolnshire*. BATEMAN, M D, BUCKLAND, P C, FREDERICK, C D and WHITEHOUSE, N J (editors). Quaternary Research Association Field Guide.

WHITEHOUSE, N J, BUCKLAND, P C, BOSWIJK, G. and SMITH, B M. 2001. The Ontology of Thorne and Hatfield Moors. 195– 198 in *The Quaternary of East Yorkshire and North Lincolnshire*. BATEMAN, M D, BUCKLAND, P C, FREDERICK, C D and WHITEHOUSE, N J (editors). Quaternary Research Association Field Guide.

WHITEHOUSE, N J, BUCKLAND, P C, BOSWIJK, G. and SMITH, B M. 2001. Hatfield Moors (SE 7006). 179–183 in *The Quaternary of East Yorkshire and North Lincolnshire*. BATEMAN, M D, BUCKLAND, P C, FREDERICK, C D and WHITEHOUSE, N J (editors). Quaternary Research Association Field Guide.

WHITEHOUSE, N J, BUCKLAND, P C, WAGNER, P and SMITH, B M. 2001. Lindholme Island (SE 708063). 185–193 in *The Quaternary of East Yorkshire and North Lincolnshire*. BATEMAN, M D, BUCKLAND, P C, FREDERICK, C D and WHITEHOUSE, N J (editors). Quaternary Research Association Field Guide.

WHITEHOUSE, N J. 2004. Mire ontogeny, environmental and climate change inferred from fossil beetle successions from Hatfield Moors, eastern England. *The Holocene,* Vol. 14, 79–93.

WHITEHOUSE, N J. and SMITH, D N. 2004. 'Islands' in Holocene forests, implications for forest openness, landscape clearance and 'culture-steppe' species. *Environmental Archaeology,* Vol. 9, 203–212.

WRAY, D A. 1927. The Barnsley Coal and its variations. 127 in *Summary of Progress for 1926.* Geological Survey of Great Britain (London: Her Majesty's Stationery Office.)

WRAY, D A and TRUEMAN, A E. 1931. The non-marine lamellibranches of the Upper Carboniferous of Yorkshire and their zonal sequence. 70 in *Summary of Progress for 1930*. Geological Survey of Great Britain (London: Her Majesty's Stationery Office.)