British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Scarborough Geological Watching Brief: Toll House Shaft Site, Castle Hill SSSI

Geology and Regional Geophysics

Internal Report IR/13/025

BRITISH GEOLOGICAL SURVEY

Geology and Regional Geophysics

INTERNAL REPORT IR/13/025

Keywords

Scarborough; Castle Hill, Toll House Shaft; Geology; Callovian-Oxfordian, Middle Jurassic, SSSI

National Grid Reference

Centre point: E ^{5}05209.71 N. ^{4}88927.96

Map

Sheet 54, 1:50 000 scale, Scarborough

Front cover

Oblique aerial view of Castle Hill looking NW; courtesy of Arup (photograph courtesy of www.petersmith.com)

Bibliographical reference

Powell, J H and Riding, J B. 2013. Scarborough Geological Watching Brief; Toll House Shaft Site, Castle Hill SSSI *British Geological Survey Internal Report*, IR/13/025. 48 pp + figures.

Scarborough Geological Watching Brief: Toll House Shaft Site, Castle Hill SSSI

J H Powell and J B Riding

Contributor

B M Cox

Editors

A S Howard & J Ford

Keyworth, Nottingham British Geological Survey 2013

BRITISH GEOLOGICAL SURVEY

The full range of our publications is available from BGS shops at Nottingham, Edinburgh, London and Cardiff (Welsh publications only) see contact details below or shop online at www.geologyshop.com

The London Information Office also maintains a reference collection of BGS publications, including maps, for consultation.

We publish an annual catalogue of our maps and other publications; this catalogue is available online or from any of the BGS shops.

The British Geological Survey carries out the geological survey of Great Britain and Northern Ireland (the latter as an agency service for the government of Northern Ireland), and of the surrounding continental shelf, as well as basic research projects. It also undertakes programmes of technical aid in geology in developing countries.

The British Geological Survey is a component body of the Natural Environment Research Council.

British Geological Survey offices

BGS Central Enquiries Desk

Tel 0115 936 3143 Fax 0115 936 3276

email enquiries@bgs.ac.uk

Environmental Science Centre, Keyworth, Nottingham NG12 5GG

Tel 0115 936 3241 Fax 0115 936 3488

email sales@bgs.ac.uk

Murchison House, West Mains Road, Edinburgh EH9 3LA

Tel 0131 667 1000 Fax 0131 668 2683

email scotsales@bgs.ac.uk

Natural History Museum, Cromwell Road, London SW7 5BD

Tel 020 7589 4090 Fax 020 7584 8270

Tel 020 7942 5344/45 email bgslondon@bgs.ac.uk

Columbus House, Greenmeadow Springs, Tongwynlais, Cardiff CF15 7NE

Tel 029 2052 1962 Fax 029 2052 1963

Maclean Building, Crowmarsh Gifford, Wallingford OX10 8BB

Tel 01491 838800 Fax 01491 692345

Geological Survey of Northern Ireland, Colby House, Stranmillis Court, Belfast BT9 5BF

Tel 028 9038 8462 Fax 028 9038 8461

www.bgs.ac.uk/gsni/

Parent Body

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon SN2 1EU

Tel 01793 411500 Fax 01793 411501

www.nerc.ac.uk

Website www.bgs.ac.uk

Shop online at www.geologyshop.com

Foreword

The British Geological Survey (BGS) was commissioned (2012-2013) to undertake a geological watching brief on behalf of Arup for Yorkshire Water Services for the site investigations and shaft sinking for a new sewage pumping station at Toll House, Castle Hill. Additional scientific studies were funded by the BGS.

The general site at Castle Hill, and more specifically South Toll House Cliff, is a geological Site of Special Scientific Interest (SSSI) as designated by Natural England. It provides an excellent section through the Middle and Upper Jurassic succession of the upper Osgodby Formation and overlying Oxford Clay Formation. Furthermore, the site is of significant current and historical scientific interest as it was studied and extensively collected down to the sea-level (prior to the construction of Marine Drive) by pioneering geologists who established the ammonite biostratigraphy of the Callovian to Oxfordian sucession in the Cleveland (Yorkshire) Basin. The lower exposures have not been visible since the late 19^{th} century, hence the importance of recording the site investigation borehole cores and the geology exposed during shaft excavations.

The scientific results of the site investigation boreholes at the Toll House shaft site are integrated in the report with information obtained during the incremental excavation of the shaft to ca. -20 m OD depth, together with additional borehole data from the surrounding Castle Hill area.

Acknowledgements

A large number of individuals in BGS and Arup have contributed to the project. Of the many individuals who have contributed to the project we would particularly like to thank the following:

Dr Beris Cox for identifying the macro-fossils, especially ammonites, from the boreholes and shaft.

Dr Andy Howard (BGS) for reviewing the report and advising on Jurassic trace fossil assemblages.

Jon Ford (BGS) for supporting additional scientific studies and comments on the manuscript.

Tom Casey, Arup (Leeds), for initiating the project and advising on the engineering geology at all stages of the study.

Helen Miles, Arup (Leeds) for arranging and supervising site visits, collecting and photographing bagged samples in the shaft.

Giuseppe La Vigna, Site Agent, Morgan Sindall Gronmij for arranging access to the site and H&S briefings.

Engineers and contractors at Ward Burke, for access to the shaft and supervising H&S in the shaft.

Dr Stuart Gowland, Ichron Ltd, for information on Jurassic trace fossils.

Peter Smith (www.petersmith.com) for use of oblique aerial photographs.

Paul Witney (BGS) for digital photography of the core and the BGS Core Store team for delivery of the core to BGS and core slabbing.

Dr Ian Wilkinson (BGS) for identification of the foraminifera in Figure 11.

Becky Bedson, Pretinder Prem and Lynne Riley (BGS) for project support and contractual advice.

Contents

FIGURES

Figures, including photographs, are at the end of the report.

Summary

This report presents the results of a study by the British Geological Survey (BGS) to carry out a 'Geological Watching Brief' for the Scarborough Revised Bathing Water Directive works at the Toll House Pumping Station shaft site, Scarborough, a designated geological Site of Special Scientific Interest (SSSI). The research was carried out on behalf of Arup for Yorkshire Water Services Ltd. during the sinking of the Toll House shaft in spring/summer 2013, and included conjunctive studies of site investigation borehole cores and gamma-ray logs drilled at the site and the surrounding area in 2011.

Study of the site investigation boreholes cores, ganmma-ray logs and shaft geology provided new information on the Jurassic Callovian-Oxfordian succession, only part of which is currently exposed at the South Toll House Cliff geological SSSI.The geological findings have both scientific and historical-scientific value, because the lower part of the Callovian succession on the lower foreshore, which was studied by pioneering 19th century geologists, has not been visible since the construction of Marine Drive (1897-1907) and more recent rock-armouring of the foreshore.

Site investigation borehole cores from the site were slabbed and curated at BGS Keyworth. The following succession (up to 41 m thick) was proved in the boreholes, in downward sequence: the lower part of the Lower Oxfordian Oxford Clay Formation (Weymouth Member); the Callovian Osgodby Formation, including the Hackness Rock, Langdale and Red Cliff Rock members); the Early Callovian Cayton Bay and Cornbrash formations, and in one borehole, the underlying Bathonian Scalby Formation. The slabbed core was sampled for palynology, macrofossils and petrology.

The upper part of the succession, from the Oxford Clay Formation down to the level of the Red Cliff Rock Member (Osgaodby Formation) was also proven in the shaft excavation that terminated at -20 m OD depth. The Osgodby Formation (sandstone and berthierine ooidal sandstone) that makes up most of the succession is interpreted as a bioturbated lower- to upper-shoreface, silty sandstone similar to lithofacies described from the Lower Fulmar Member of the Central Graben, North Sea. It overlies a condensed transgressive marine unit, the Lower Callovian Cornbrash Formation and the attenuated Cayton Clay Formation. The Early Callovian marine transgression flooded the low-gradient alluvial plain represented here by the underlying Upper Bathonian Scalby Formation (Long Nab Member).

The presence of latest Bathonian to Early Callovian palynofloras in the uppermost Scalby Formation indicate that there was no great time gap between the deposition of this paralic unit and the overlying marine Cornbrash Formation (also Early Callovian in age).

Condensed sequences, deposited during marine transgressions, rich in berthierine (an iron-rich aluminous silicate) ooids and abundant shelly fossils including oysters, ammonites and belemnites, are represented by the Cornbrash Formation and Hackness Rock Member at the base and top of the Callovian succession, respectively. The intervening sandstones of the Osgodby

Formation (Red Cliff Rock and Langdale members) are extensively bioturbated by a diverse ichnofauna (trace fossil) assemblage that scavenged the sandy substrate rich in amorphous organic matter, thereby destroying most of the sedimentary structures. Sedimentation rates were slow, with long sediment residence time on the sea-floor resulting in a high bioturbation index.

Newly recorded pyrite ooids in the lower Osgodby Formation sandstones are interpreted as being formed in anoxic lagoons in the nearshore zone as a result of a fluctuating redox interface; ooids were subsequently swept offshore during storm surge-ebb events.

Warm water dinoflagellates of Tethyan Ocean affinity *(Scriniodinium crystallinum)* in the lower part of the Oxford Clay Formation indicate an Early Oxfordian age, confirmed by the presence of the zonal ammonite species *Quenstedoceras mariae* in the lowermost siltstone. Warm water dinoflagellates may indicate thermal warming and ocean water expansion during Mariae Zone time that led to a global sea-level rise and associated widespread marine transgression.

Shaft excavations revealed a new major fault, the Toll House Fault, trending ca. 350 ºN, downthrowing the Hackness Rock Member about 15.5 m to the east. The fault appears to control the eastern side of Castle Hill and is responsible for the anomalously high dip in the extant South Toll House Cliff, as a result of local fault drag. The Toll House Fault is interpreted to be a splay fault bifurcating off the main Castle Hill Fault, which together form the western bounding faults of the Peak Trough, a graben-like structure that extends northwards, offshore. Faulting along Marine Drive, parallel to the cliff may explain some of the anomalies between the stratigraphy proved in the borehole cores compared to that reconstructed from Victorian records of the formerly exposed lower cliff and foreshore.

The study demonstrates the value of a multidisciplinary geological approach, and the additional value of collaboration between BGS, major utility companies, and civil engineering schemes in recording, updating and curating geological information for the nation. In addition to its scientific value, such information helps to upgrade the national geological base map/model, and offers information for future researchers and civil engineering schemes. Although the Toll Hose site has special significance in respect of its SSSI status, we recommend that other major civil engineering infrastructure schemes develop collaborative studies with the BGS

1 Introduction

This report summarises the results of a study by the British Geological Survey (BGS) on behalf of Arup for Yorkshire Water Services to carry out a 'Geological Watching Brief' for the Scarborough Revised Bathing Water Directive works at the Toll House Pumping Station shaft site, Scarborough. The overall aim of the greater engineering scheme is to increase the storm water storage capability and to improve the quality of the associated discharges to help Scarborough's beaches achieve 'Excellent' standard as defined in the revised EU Bathing Water Directive.The Toll House site constitutes all or part of a geological Site of Special Scientific Interest (SSSI) extending southwards along the cliff from North Bay to south Toll Hose Cliff [TA $^{5}048^{4}893$; TA $^{5}051^{4}894$; TA $^{5}046^{4}892$; TA $^{5}048^{4}892$], as designated (1992) by Natural England that required geological monitoring, logging and assessment of site investigation borehole cores and the geology of a deep shaft at Toll House. The study included slabbing and digital photography of the cores, macro- and micro-fossil biostratigraphical determinations and sedimentological description of selected borehole and shaft geology in order to characterise the Jurassic (Callovian to Lower Oxfordian) geology of site. The report will act as a permanent record of the geology at the Toll House SSSI site for Natural England and others. Macro- and micro-fossil samples and appropriate representative cores are curated at the BGS headquarters at Keyworth, Nottingham.

The Toll House site situated on the south-east flank of Castle Hill, Scarborough is of special scientific interest because of its excellent (now partial) exposure of the Callovian to Oxfordian sedimentary succession comprising, at outcrop, in upwards sequence: the upper part of the Osgodby Formation, including the Hackness Rock Member, and the lower part of the Oxford Clay Formation (Weymouth Member), which, in turn, is overlain by inaccessible cliff exposures of the Corallian Group. Historically, the site is of great interest because it was one of the most intensively sampled localities by Victorian geologists who established the outline ammonite biostratigraphy of the Callovian to Oxfordian stages in the Cleveland (Yorkshire) Basin, at a time prior to construction of Marine Drive and more recent rock armouring of the formerly visible exposures on the lower foreshore. Ammonites collected from the lower part of the Oxford Clay Formation and Osgodby Formation, especially the Hackness Rock Member, at this locality probably include type specimens held in museums such as *Cardioceras Scarburgiceras scarburgense* (Young & Bird 1828) from the Mariae Zone (Lower Oxfordian; Oxford Clay Formation). Consequently, the opportunity to study both borehole core from the Oxford Clay Formation and the underlying Callovian succession comprising, in descending sequence, the Osgodby, Cayton Clay and Cornbrash formations (terminating in the Bathonian Scalby Formation) combined with incremental sampling of the shaft excavation, presented an important opportunity to study the succession and to record it for posterity. Previous site investigation studies and offshore seismic studies for the existing sewage outfall during the 1980's demonstrated faulting offshore from Castle Hill (Powell and Reay, 1982).

The lead geologist for the project was Dr John Powell (JHP), who carried out stratigraphical and sedimentological logging of the site investigation borehole cores, petrography of thin sections, and sampling of the shaft geology. Dr Jim Riding (JBR) was responsible for borehole sampling for micro-palaeontology and subsequent micro-palaeontological (dinoflagellate) analyses. Dr Beris Cox identified ammonites and other macrofossils collected from both the borehole cores and shaft.

Site investigation boreholes drilled on behalf of Arup and Yorkshire Water Services were logged for their geotechnical parameters prior to selection and transport of the cores to BGS Keyworth for slabbing, digital photography and detailed geological study. Consequently, some sections of the core had been removed for geotechnical testing and were not available to the BGS study. During the subsequent sinking of the shaft, JHP was able to visit the shaft site on five occasions to collect specimens from the rock floor/flank of the shaft and to take structural measurements under supervision by staff from Arup, Morgan Sindall Grontmij and Ward Burke. Additional borehole information for the wider Castle Hill site was made available by Arup, which has allowed the stratigraphy and structural geology of the area to be better understood.

Significant new geological findings have arisen from the study, including new information about the sedimentation, biostratigraphy and structural geology of the Toll House site, as detailed below.

2 Site Location and Access

The Toll House site (NGR E ^{5}05209.71 N. ^{4}88927.96) is located on the south-east side of Castle Hill below Castle Cliff (British Geological Survey, 1998a; 1998b). The studied site included the main shaft for the new Toll House Pumping Station which will have a storm water capacity of 4000 m^3, and an adjacent connection chamber located a few metres to the south. The site lies just to the north of well known locality South Toll House Cliff (Page, in Cox and Sumbler, 2002) that exposes the upper part of the Osgodby Formation sandstone (Langdale Member) and the uppermost unit, the Hackness Rock Member, which, in turn, is overlain by the Oxford Clay Formation (Figure 1).

Access to the shaft during sinking was subject to the strict health and safety regimes of the site operators and BGS. Access to the shaft was by a man-cage lifted by a crane. Geological investigations were limited to five visits of about 45 minute's duration to allow JHP to sample the bedrock and to take structural measurements. Sampled depth intervals in the shaft are:

Sampled depth at base of shaft relative to Ordnance Datum in Toll House Shaft	Date of sampling
- 1.5 m OD	12/02/2013
- 3.0 m OD	21/02/2013
- 14 m OD	03/04/2013
- 17 m OD	24/04/2013
- 20 m OD	14/05/2013

Additional ad-hoc rock samples were taken by Helen Mikes (Arup) at critical depths.

3 Importance of the Toll House SSSI site

The geological and historical importance of the Toll House SSSI site (also known as South Toll House Cliff) is due to the excellent current, and formerly more extensive, exposures of the sedimentary rocks encompassing the Callovian Stage and the Lower Oxfordian Substage. At outcrop, the upper part of the Osgodby Formation, termed the Langdale Member (sandstone) (Coronatum Zone) forms a small cliff [TA 0515 8885] north-west of Toll House, and is capped by a harder iron-rich (berthierine ooidal) calcareous sandstone, the Hackness Rock Member (Athleta Zone and Lamberti Zone) which forms a prominent ledge (Figure 2). Although largely grassed over, the overlying Oxford Clay Member (Mariae Zone; Lower Oxfordian) is also poorly exposed. This stratigraphy and sedimentology of this section has been studied by many authors (see below) and has yielded biostratigraphically important ammonite specimens some of which represent type specimens now located in museums (Page, in Cox and Sumbler, 2002), and includes the Callovian-Oxfordian stage boundary. This exposure dips northwards at about 5 - 8 º NNE, so that the same succession was encountered in the site investigation boreholes drilled for the Toll House Pumping Station and in the shaft itself.

Consequently, these engineering works offered a valuable opportunity to record, describe and study the same succession, at depth, where the rocks are relatively unweathered. Perhaps more significantly, the opportunity to study the lower part of the succession as revealed by the boreholes (to ca. 40 m depth) and in the shaft, afforded the first opportunity to study this part of the succession since the mid 19th century, prior to the construction of Marine Drive and more recent rock armouring of lower cliff and foreshore below the road.

It was these former exposures of the lower part of the Osgodby Formation that allowed the pioneering geologists William Smith and his protégé and nephew John Phillips to understand the geology of Scarborough in its regional context. Following on from Smith's early geological map of Yorkshire, Phillips refined the geology and published (1829-1832) an elegant cross-section of the Yorkshire coast including much detail of Toll House to Castle Hill section (Figure 3), which shows clearly the Osgodby Formation (then known as the 'Kelloway Rock') dipping to the north-east below the overlying Oxford Clay. To the north of Castle Hill, Phillips also illustrated the 'Cornbrash' and 'Upper Shales and Sandstone' (Scalby Formation) below the 'Kelloways Rock' (Osgodby Formation).

Victorian geologists were keen collectors of ammonites and other shelly fauna, such as bivalves and belemnites, from these rocks in order to establish a biostratigraphical zonation that would allow correlation of the Yorkshire succession with coeval rocks in central and southern England (Young and Bird, 1822; Leckenby, 1859; Wright, 1860; Huddleston, 1876). These ammonite schemes were later refined by Brinkmann, 1926, Buckman (1909-30; 1913) and commented on by Arkell (1933;1945), thereby establishing that the Osgodby Formation (sandstone) of the Cleveland (Yorkshire) Basin is broadly equivalent to the mudstones of the Lower and Middle Oxford Clay Formation of central and southern England, and furthermore, that silt and mud (Oxford Clay Formation) were deposited in the Cleveland Basin, north of the Market Weighton High, only later in Early Oxfordian times. Consequently, the Oxford Clay Formation seen at Castle Hill is equivalent to the upper unit, the Weymouth Member, of the Oxford Clay Formation of southern England (Fox-Strangways, 1892; Fox-Strangways and Barrow, 1915; Cox et al., 1993).

More recently, detailed and wide ranging studies by Wright (1968; 1977) have revealed a more complex sedimentary history during Callovian times. Using detailed analysis of the ammonites and other shelly faunas, and logging of the Osgodby Formation, Wright (1968) showed that there are significant time gaps and erosional events (hiatuses) separating the three members of the Osgodby Formation (Kellaways Rock Member, Langdale Member and Hackness Rock Member, in upward sequence). Wright's stratigraphical studies were further refined by Cox, (1988) and Page (1989); the latter author introduced a number of new lithostratigraphical terms some of which have not gained wide acceptance. Part of the Upper Jurassic succession (Coralline Oolite Formation) on the north side of Castle Hill and the southern end of North Bay is described in Rawson and Wright (2000; Itinerary 7). A sedimentological study of the Hackness Rock Member, based on the Toll House exposures (Williams, 2002) showed that microfacies in this condensed unit represented diverse depositional sub-environments. The South Toll House cliff and adjacent localities were also described in the Middle Jurassic Joint Conservation Review of Great Britain (Page, in Cox and Sumbler, 2002), highlighting the scientific importance of the exposures.

4 Borehole Investigations and methodology

Prior to excavating the Toll House Pumping Station shaft a number of site investigation boreholes were drilled sub-parallel to Marine Drive in the vicinity of the shaft site and associated engineering works (Figure 4). In addition, four deep cored boreholes were drilled from the top of Castle Hill and adjacent fault blocks, located to the north-west of the site, to prove the geology below Castle Hill for a projected sewage tunnel that was not taken forward. Borehole records (logged by JHP) from the 1980's, for the existing sewage outfall were also available in the BGS records (Powell, 1980; Powell and Reay, 1982).

The site investigation boreholes drilled for the current engineering works were initially in inspected by JHP at the Yorkshire Water Services store at Burniston. Four representative borehole cores (BH1-3-02; BH1-3-03C; BH1-3-04; and BH2-3-01) were selected and transported to the BGS core store where they were slabbed, cleaned and logged geologically by JHP. High resolution digital photographs were taken of the slabbed core (Appendix 1); the core was sampled for micropalaeontology and petrology by JBR and JHP. Non-curated halves of the cores were split parallel to the bedding planes to obtain macro-fossils specimens and representative examples of trace fossils (burrows).

Some of the core was not available because selected lengths had been extracted for engineering geology testing prior to geological investigations by BGS. However, the four curated boreholes provide overlapping representative core for the Callovian to Lower Oxfordian succession.

5 Shaft Investigations

Geological investigations during sinking of the shaft were limited to five visits of around 45 minutes duration (see 2 above). JHP was able to sample the rock from the base of the shaft and ca. 0.75 m of exposed rock in the wall adjacent to the cutting shoe. Ongoing excavation of the shaft by rock hammer meant that, at times, it was difficult to determine sedimentary bedding, but structural measurements were taken where feasible. In addition to the samples taken by JHP, Helen Miles (Arup) collected ad-hoc samples from the base of the shaft on a weekly basis; these were backed up by a digital photographic record that proved to be important when contrasting lithologies were exposed either side of the new Toll House Fault (see 7.4 below). The fault line was surveyed by theodolite by Ward and Burke during the excavations.

Hand samples taken by JHP were cleaned and curated at BGS. The final samples were taken on 14.05.2013 at -20 m OD depth, prior to final cementing of the shaft floor.

6 Sedimentology, biostratigraphy and petrology

6.1 GEOLOGICAL OVERVIEW OF CASTLE HILL

Castle Hill is a downfaulted (east) outlier of Middle and Upper Jurassic strata that forms a promontory separating South Bay from North Bay (British Geological Survey, 1998a; 1998b). Major faults, with up to 80 m displacement, downthrow Upper Jurassic rocks against Middle Jurassic rocks, but the structure is complicated by two splay faults that bring the Middle Jurassic rocks (Scalby Formation) and the Cornbrash Formation marker bed high up in the cliff against the Oxford Clay Formation to the to the east (Figure 1). The shaft excavation also proved a previously unknown fault (Toll House Fault) orientated ca. 350 º N, sub-parallel to Marine

Drive, which downthrows the Oxford Clay and Cornbrash formations ca. 15.5 m to the east, thus defining the eastern margin of Castle Hill (see details below).

The general structure of Castle Hill is a shallow syncline plunging to the east, with higher dips (ca. 5º to 8º NNE) at South Toll House Cliff, and to the north end of Castle Hill (ca. 5 º SSE). The anomalously high structural dip seen in Osgodby Formation at South Toll House Cliff (Figure 2) is now considered to be due to fault drag on the previously unrecorded Toll House Fault. The stratigraphically highest beds exposed on the summit of Castle Hill comprise the lower part of the Hambleton Oolite Member (Coralline Oolite Formation; Corallian Group) (Wright, 1983); these relatively hard beds have protected Castle Hill from erosion.

Seen in a regional context, the faults defining Castle Hill form part of the NNW-trending Peak Trough and associated faults that have been shown to be active, in the offshore sector east of Whitby, since Triassic times (Milsom and Rawson, 1989).

The steep slopes of Castle Hill cliff between South Toll House Cliff, and the north end of the promontory are subject to landslip in the form of rockfall and scree from the jointed and fractured faces of the Lower Calcareous Grit and the Coralline Oolite formations that overlie the softer Oxford Clay Formation. Fallen blocks and scree material, probably deposited during late Pleistocene to Holocene erosion of the palaeo-cliff, were penetrated up to 8 m below the ground surface in the site investigation boreholes sub-parallel to Marine Drive.

6.2 STRATIGRAPHY AND SEDIMENTOLOGY OF THE TOLL HOUSE PUMPING STATION BOREHOLES

This section is based largely on the analysis of Borehole 1-3-03C that proved the succession from the Oxford Clay Formation down to the Cornbrash Formation and topmost Scalby Formation, supplemented by three additional boreholes that proved critical parts of the succession (Table 1). Geophysical wireline gamma-ray logs, provided by Arup, have assisted in correlation of the boreholes (Figure 4). The location of the boreholes and summary lithological and gamma-ray logs of these boreholes provided by Arup are shown in Figure 4; some of the stratigraphical boundaries shown in these logs have been reinterpreted following detailed analysis of the core. The curated boreholes, located from south to north, with the formations penetrated, in descending order are listed in Table 1.

Borehole Number	**Ground Level (m)**	**Depths logged (m) (by BGS)**	**Lat: long**	**Formations penetrated**
BH 1-3-04 Toll House	+8.46 OD	27.35 - 36.00	E: 505189.36 N: 488892.65	Rock Fall /Scree Osgodby Formation Cayton Clay Formation (?) Cornbrash Formation Scalby Formation (upper)
BH 1-3-03C Toll House	+8.68 OD	4.20 - 41.70	E: 505209.71 N: 488927.96	Rock Fall/Scree Oxford Clay Formation (lower) Osgodby Formation Cayton Clay Formation (?) Cornbrash Formation Scalby Formation (upper)

BH 1-3-02 Toll House	+9.42 OD	12.50 – 17.50	E: 505212.78 N: 488954.57	Rock Fall/Scree Oxford Clay Formation (lower) Osgodby Formation (upper)
BH 2-3-01 Toll House	+8.83 OD	17.50 - 25.00	E: 505245.07 N: 489064.11	Rock Fall/Scree Oxford Clay Formation (lower) Osgodby Formation (upper)

Table 1. Summary of the Toll House Site Investigation Boreholes used in this study.

6.2.1 Stratigraphical succession

The stratigraphical succession proved in the boreholes is described in ascending stratigraphical order (i.e. incremental geological history; base to top). This account is based primarily on the most complete core, BH 1-3-03C (Figure 4) except where noted. Depths refer to drilled depths from ground surface in BH1-3-03C, except where noted for other boreholes (Figures 5-8). Borehole cores are also illustrated in Appendix 1.

6.2.1.1 Scalby Formation (Middle Jurassic: Bathonian): 41.55 – 41.62 m depth

Only the topmost 0.07 m of the Scalby Formation was proved at the base of the borehole from 41.55 – 41.62 m. It consists of pale grey, non-calcareous mudstone with sparse plant fragments. Borehole 1-3-04 (Figure 8) proved a thicker succession from 34.80 – 35.60 m consisting of pale grey mudstone with sparse plant fragments overlain by structureless, fine-grained, non-calcareous sandstone. The boundary with the overlying Cornbrash Formation is irregular and erosional.

The structureless nature of the sandstone suggests pedogenic alteration, and the presence of finely comminuted plant fragments indicates deposition in a non-marine, alluvial floodplain environment. In contrast to the boundary seen at outcrop in Cayton Bay, to the south, there is no evidence of downward penetrating *Thalassinoides* burrows at the base of the Cornbrash Formation (Wright, 1968; Riding and Wright, 1989; Powell 2010).

6.2.1.2 Cornbrash Formation (Middle Jurassic: Callovian) 40.80 – 41.55 m depth

The Cornbrash Formation is thinner in these boreholes (0.75-0.95 m) compared to reported outcrops in North Bay (1.18 m; Wright, 1977; Page, in Sumbler and Cox, 2002). The lower part (0.22 m) comprises brown and grey sideritic, calcareous mudstone with bioclastic coarser burrow-fill, comminuted shell fragments and sparse oysters (*Ostrea* sp.) (Figure 10). This passes up to pale grey, medium-grained sandstone with berthierine ooids and rounded intraclasts of black calcareous mudstone with small berthierine ooids and small shell fragments; sparse encrusting serpulid worms and bryozoans are present. The uppermost 0.30 m consists of light grey to medium light grey, bioclastic limestone with dispersed berthierine ooids. The rock fabric is highly bioturbated (*Thalassinoides*); other burrows are backfilled with grey calcareous mudstone (siderite); oysters (*Ostrea* sp.; *Lopha* sp.) are common along with *Trigonia* sp. and other bivalve fragments. Fragmented ammonite shells and belemnite guards are occasionally present. The upper boundary with the Cayton Clay Formation is poorly preserved in BH 1-3-03C, but is sharp in BH 1-3-04.

In thin section (Figure 11) calcareous foraminifera (*Lenticularia* sp.) are present, confirming an early Callovian age. Berthierine ooids are commonly replaced by ferroan calcite, although much of the shell material is preserved as non-ferroan calcite. Sub-angular quartz is present, and pyrite spheres or framboids (so-called 'raspberry-like' clusters) are common in the sparry calcite matrix.

6.2.1.3 CAYTON CLAY FORMATION (MIDDLE JURASSIC; CALLOVIAN: HERVEYI ZONE) 40.60 – 40.80 M DEPTH

This thin formation is poorly preserved in the boreholes, probably on account of its soft mudstone lithology which is prone to re-drilling or flushing. However, fragments of brownish grey mudstone with light grey, very fine-grained sandstone with micaceous siltstone laminae were preserved in BH 1-3-03 C over an interval of about 0.20 m. A similar thickness (0.25 m) was proved in BH 1-3-04. No macrofauna was recovered from the core.

The Cayton Clay Formation (formerly known as 'Shales of the Cornbrash') is also reported to be poorly exposed in North Bay (Wright, 1977; Page in Cox and Sumbler, 2002) where the basal 0.10 m of dark grey, silty clay has yielded abundant bivalves including *Meleagrinella braamburiensis* (Phillips) and *Modiolus bipartitus* (J. Sowerby) (Page, 1989).

6.2.1.4 OSGODBY FORMATION (MIDDLE JURASSIC: CALLOVIAN: KOENIGI TO LAMBERTI ZONES) 11.70 – 40.60 M DEPTH

The greater thickness of the shaft is in the Osgodby Formation, which ranges in age from the Koenigi to Lamberti zones of the Callovian Stage, spanning about 3.5 million years. Formerly known as the Kelloways Rock (Phillips, 1829-32) and later as the Kellaways Rock (see Arkell 1933 for discussion) it was formally defined by Wright (1968), who subdivided the formation into three members, in upward sequence, the Kellaways Rock Member, Langdale Member and Hackness Rock Member. Subsequently, Page (1989) re-named the lower member to the Red Cliff Rock Member to distinguish it from the Kellaways Rock of southern England.

Wright (1968; 1977) showed that there is considerable lateral variation in the thickness and distribution of the three constituent members, which are locally separated by intraformational depositional hiatuses or erosion surfaces. The succession at Toll House, Castle Hill is shown in Figure 5 of Wright (1968), but this is based largely on an earlier description of the foreshore and lower cliff by Huddleston (1876) prior to the construction of Marine Drive. The figure was supplemented by a description based on the succession seen in the cliff below Rutland Terrace in North Bay (Wright, 1968, section 4). Consequently, there is no wholly reliable extant section for the Osgodby Formation at the South Toll House Cliff site. The new cored borehole records are, therefore, highly significant, especially in light of the discovery of the new Toll House Fault, which downthrows the Osgodby Formation to the east (see below), thereby possibly introducing a repetition of the strata as formerly seen in the Toll House foreshore cliff in the 19th century. With this possibility in mind, the section redrawn by Wright (1968) in Figure 5 (based on Huddleston, 1876) seems to bear little relationship to the Osgodby Formation succession proved in the boreholes. For instance, the feature-forming fine- and medium-grained, sandstone beds ca. 5.8 m thick, including a medium-grained sandstone bed with ammonites in the upper part of the Red Cliff Rock Member have not been identified in the borehole cores.

The lower boundary with the Cayton Clay Formation is sharp; the basal Osgodby Formation sandstone is fine- to medium-grained with ripple cross-lamination and thin clay drapes; in the basal 0.20 m, a sideritised ammonite was found at 40.45 m depth, and calcite belemnite guards are occasionally present. The overlying sandstone consists of brownish grey, medium-grained sandstone with abundant amorphous organic matter and dispersed black, concentric pyrite ooids up to 0.5 mm in diameter (Figures 12,13). A characteristic feature of the core is the high bioturbation index with a range of trace fossil burrows including: *Teichichnus*, *Phoebichnus, Siphonites, Planolites, Skolithos, Diplocraterion and Chondrites* (Figure 12). Intensive burrowing is often seen to show sequential tiering (Howard, 1985; Gowland, 1996; Taylor and Gawthorpe, 1993; Taylor *et al*, 2003) i.e. reworking or re-burrowing across previously formed burrows. Consequently, the original primary sedimentary structures (e.g. ripples, cross-lamination and bedding) are generally destroyed. Exceptions to this are intervals between 38.10 to 38.20 m where discrete parallel lamination is preserved in sandstone interbedded with siltstone, and at 34.45 m, 34.48 m and 32.65 m. Black pyrite ooids become more common upwards from about 34.50 m. Ovoid, medium-grey siderite concretions, 0.08m in diameter, are present at 34.80 m and 34.48 m (Figure 12). A gradational upward decrease in overall grain size occurs at about 31.20 m depth, also accompanied by fewer dispersed pyrite ooids. This level may mark the boundary between the lower member, the **Red Cliff Rock Member** (**Kellaways Rock**) and the overlying **Langdale Member**. However, the change is gradational, and the feature-forming (better cemented?) beds marking this boundary in the former South Toll House Cliff in Figure 5 of Wright (1968) (see above) were not seen. If this gradational boundary, as seen in the core, represents the true boundary between these members, then measured thickness (9.4 m) from the top of the Cayton Clay Formation is not significantly different from the 11.3 m thickness shown Wright's figure, especially as the lower boundary, at outcrop, appears to be an estimate.

Pyrite ooids have not previously been reported from the lower part of the Osgodby Formation. It may be that berthierine ooids described by previous authors (which are present in the Cornbrash Formation and the Hackness Rock Member) have been misidentified, especially as the cores provide unweathered fresh material that may be oxidised at outcrop. Pyrite ooids are dispersed within the bi-modal quartz sandstone (Figures 13 and 14). They comprise concentrically zoned laminae made up from individual pyrite clusters or framboids, often seeded around a quartz grain (Figure 13). The outer cortex often appears irregular or 'squeezed' between adjacent quartz grains (Figure 14). Individual or irregular clusters of pyrite framboids are also present dispersed in the matrix between the sand grains. Quartz grains are generally sub-angular and of bi-modal grain-size distribution. In hand specimen, the core appears as grey or pale grey clusters ('augen') consisting of purer quartz sand representing backfilled quartz-rich burrows surrounded by pale brown distorted laminae rich in amorphous organic matter (Figure 14).

The upper part of the sandstone-dominated Osgodby Formation, probably equivalent to the **Langdale Member**, consists of very light grey to light grey, slightly micaceous, fine- to medium-grained, slightly calcareous sandstone with medium grey wispy mudstone laminae (Figure 15). Where intersected by fractures it weathers to pale yellowish-orange sandstone. It becomes more calcareous above ca. 17 m depth, close to the boundary with the overlying Hackness Rock Member. The Langdale Member is extensively bioturbated, but the sand grain size is slightly finer and is more unimodal (better sorted) than the underlying Red Cliff Rock Member. The ichnofuana is also diverse, but the upper sandstone has a higher proportion of vertically orientated burrows especially the ichnogenera *Teichichnus, Rhizocorallium, Skolithos* and *Diplocraterion*, as well as ubiquitous *Chondrites* and *Siphonites* (Figure 15). Tier structures showing repeated, often cross-cutting, burrowing phases are common, and the sequential ordering from small *Chondrites* > *Teichicnus* > *Siphonites* > *Skolithos* > *Asterosoma* has been observed (Howard, 1985; Gowland, 1996). Shelly lags comprising small, thin-shelled bivalves and brachiopods, together with small wood fragments are present at 19.30 m and 14.50 m depth, the latter 1.5 m below the base of the overlying Hackness Rock Member. Calcite belemnite guards are occasionally present, but no ammonites were seen.

The **Hackness Rock Member** (11.70 m – 13.00 m) represents an important marker bed, 1.3 m thick, at the top of Osgodby Formation, and provided a useful marker level when interpreting the borehole cores and gamma-ray logs, and during shaft excavation (Figure 16), particularly with respect to determining the throw on the Toll House Fault. It is also the main feature of the extant South Toll House Cliff SSSI site (Figure 17). In BH 1-3-03 C the boundary with the underlying Langdale Member is gradational over 0.36 m (13.06-12.70 m); this interval is marked by an increase in the bioturbation index and carbonate content. The fine-grained, slightly calcareous sandstone is pale yellowish brown (weathered oxidised iron) close to fractures, passing to greyish orange, with pervasive burrow mottling. Occasional thin-shelled bivalves, brachiopods and belemnite guards are present at 12.70 m and 12.50 m. Ichnogenera include *Diplocraterion, Rhizocorallium, Teichichnus, Planolites, Siphonites, Chondrites* and small diameter *Thalassinoides*. Berthierine ooids are less common near the base, and are concentrated within the burrow fill (Figures 18,19). The upper part of the unit, where unweathered, is light bluish grey, calcareous fine-grained sandstone passing to sandy limestone, with intensive burrowing and relatively large berthierine ooids (up to 1 mm diameter) scattered in clusters, depending on the intensity of bioturbation. Berthierine ooids are white where altered to ferroan calcite. Patches of siderite cement are common, often infilling burrows and whole bivalve shells. Macro-fossils include bivalves, such as the oysters *Ostrea* sp.; *Lopha* sp. and *Gryphaea* sp., small rhynchonellid brachiopods, belemnite guards, ammonites, gastropods and wood fragments. Finely comminuted shell fragments are present in the upper part of unit. In BH 2-3-01 the base of the Hackness Rock Member is marked by a thin shell bed at 22.15 m depth probably representing a storm-deposited bed, above a scoured surface. This shell bed was also seen at the base of the member in BH 1-3-02 at 15.46 m depth. The shell bed is probably the same as that seen at outcrop in the South Toll House Cliff (Figure 17).

In thin section (Figure 19) the Hackness Rock Member consists of bimodal, subangular quartz, similar to the underlying sandstones, but with a higher proportion of berthierine ooids, up to 1 mm in diameter. In weathered material near to fractures the ooids are generally altered to white calcite (in hand specimen); however, in stained thin section of these weathered zones the inner laminae of berthierine and associated pyrite is occasionally preserved (Figure 19); outer laminae are altered to ferroan calcite micro-spar, which also forms much of the cement matrix.

6.2.1.5 Oxford Clay Formation (Upper Jurassic; Lower Oxfordian; Mariae Zone) 8.89 – 11.70 m depth

The Oxford Clay Formation is the highest bedrock unit proved in the boreholes and shaft excavations at the Toll House Site. Only the upper part of the Oxford Clay Formation of southern England, the **Weymouth Member**, is represented in the Cleveland (Yorkshire) Basin. It spans the Lower Oxfordian Stage, Mariae Zone, the base of which is about 163.5 Ma (Gradstein et al., 2012). Despite its lithological epithet, the formation at Castle Hill is represented by a calcareous siltstone lithology, in contrast to the softer claystone of southern England. The lower part, and the boundary with the underlying Hackness Rock Member, can be seen in the South Toll House Cliff, but is mostly grassed over. Better exposures can be seen higher in the Castle Hill cliff to the north of the site (Figure 1). The relatively steep structural dip seen in the South Toll House Cliff brings the Oxford Clay Formation down to ground level at the shaft site and farther north (Figure 2), although the site investigation boreholes along Marine Drive generally penetrated rockfall and scree material derived from the upper part of the cliff (Corallian Group) overlying the bedrock (see below).

The boundary with the underlying Hackness Rock Member is generally sharp and planar (Figure 20), but in BH 1-3-02 the boundary is irregular with upward-domed convolute structures in the basal 0.06 m, comprising pale grey and dark grey, mottled calcareous siltstone and claystone. Similar contorted laminae occur in the basal siltstone in BH 2-3-01. The lowermost 0.15 m in BH 1-3-03C comprises light brownish grey siltstone and silty mudstone with faint parallel lamination and pervasive, but poorly defined, 5 mm diameter burrows together with scattered small berthierine ooids and sparse wood fragments (Figure 20). Above 11.55 m depth it comprises light grey, calcareous siltstone, with a generally massive or faintly laminated texture. The absence of lamination is attributed to pervasive, but poorly contrasted (lithologically) burrows that have homogenised the sediment. Thin-shelled ammonites, including the zonal species *Quenstedoceras mariae*, and calcite belemnite guards are present, along with platy fragments of fish or marine reptiles and sparse thin-shelled bivalves. A characteristic feature of these lower beds is the presence of discrete circular, meandering, pyritised burrows parallel to bedding; they have a dark pyritic fill and a yellow- brown limonitic outer cortex (Figure 21). Some examples show unusual single-sided protuberances (Figure 21, inset). In thin section, cross-sections through the burrows show a dense pyrite core surrounded by 'halo' silt-grade particles in which the organic a matter is oxidised.

6.2.1.6 Rock Fall and Scree (Pleistocene to Holocene) 4.20 – 8.89 m Depth

The upper part of the core in BH 1-3-03C was not seen, but between 8.89 m and 4.20 m depth the Oxford Clay Formation is overlain by rock-fall and scree debris derived from the Corallian Group comprising calcareous spiculitic sandstones and ooidal limestones of the Lower Calcareous Grit and Coralline Oolite Formations that form the upper third of the Castle Hill cliff (Figure 1).

The rock fall deposits appear to have covered a pre-existing, lower cliff/foreshore slope cut in the Oxford Clay Formation at the Toll House shaft site. This probably occurred as a response to sea-level rise following the last glaciation in Late Pleistocene to Early Holocene times.

6.3 STRATIGRAPHY AND STRUCTURAL GEOLOGY OF THE TOLL HOUSE PUMPING STATION SHAFT

The shaft [NGR: ^{5}05213.0033, ^{4}88929.706] was excavated north of the South Toll House Cliff. JHP was able to access the geology at the base of the shaft on five occasions (see Section 2 above). The following account is based on observations at those five levels.

6.3.1 -1.5 m OD: Date 12/02/2013

The Oxford Clay Formation was exposed over much of the base of the shaft circumference (Figure 22) at this depth. Specimens of grey calcareous siltstone were collected together with fragments of thin-shelled ammonites. In the south-east of the shaft, up-dip, the upper part of the Hackness Rock Member (Osgodby Formation) was poorly exposed, but yielded shelly fossils including belemnites and bivalves (*Gryphaea* sp.) from the blue grey, burrow-mottled berthierine ooid-rich calcareous sandstone.

6.3.2 -3.0 m OD: Date 21/02/2013

At this level the whole of the Hackness Rock Member was exposed including the upper boundary with the Oxford Clay. Excellent exposures of the Hackness Rock Member included in-situ clusters of the bivalve *Gryphaea* sp. (Figure 23), burrow mottled berthierine ooid rich sandstone with bivalves and the ammonite *Kosmoceras* sp.

6.3.3 -14 m OD: Date 03/04/2013

This eventful visit proved the presence of a major geological fault cutting a narrow sector on the eastern side of the shaft. Extensively burrow-mottled, fine- to medium-grained sandstone (Osgodby Formation) on the upthrow side of the shaft contrasted with medium grey calcareous siltstone (Oxford Clay Formation) on the downthrow side (Figure 24). Although the fault trace on the base of the shaft was difficult to determine due the presence of water and rock spoil, the fault was more clearly seen at the base of the shaft cutting edge. Fracturing within the harder Osgodby Formation adjacent to the fault was shown by orange and brown oxidative weathering of the ferruginous sandstone. A tentative orientation of ?060 º N (but see below) was estimated for fault trace, with a downthrow of at least 15 m to the east (the variation with the fault orientation measured on 24.04.13 may be a result of compass deviation by the metal at the foot of the cutting shoe). The Oxford Clay Formation at this level yielded fragmentary Lower Oxfordian ammonites that confirmed the presence of the fault.

6.3.4 -17 m OD: Date 24/04/2013

Deepening of the shaft to -17 m depth confirmed the presence of the fault downthrowing the Oxford Clay Formation and the Hackness Rock Member against the Osgodby Formation (Figure 25). The orientation of the fault trace in the bottom of the shaft was revised to between 350º N and 010º N (but see below). The Hackness Rock at this depth is highly fractured with abundant calcite mineralisation along the fracture/fault planes; pyrite crystals are also present. Sub-vertical fracture/fault plane surfaces of the unweathered blue-grey berthierine ooidal sandstone are weathered (oxidised) to orange, brown and yellow as a result of the flow of brackish water along the fractures. Sparse ammonites were collected from the Hackness Rock Member at this level. On the side of the shaft opposite the fault trace, the middle to lower part of the Osgodby Formation sandstone was seen dipping at about 22 º to 110 º N, i.e. dipping at approximately right angles to the fault (Figure 25); the anomalously high dip is attributed to localised drag of the upthrow (footwall side) of the fault. GPS did not function in the shaft at this depth, but a point due east of the shaft wall on Marine Drive is: N: 54 º 17’ 06.5’’; E: 000 º 23’ 06.8’’. The orientation of the fault was surveyed using a theodolite at the base of the shaft on this date/depth by contractors Ward Burke; the co-ordinates for the fault trace are between [^{5}05213.0033, ^{4}88929.706] and [^{5}05207.757, ^{4}88918.890] (Helen Miles (Arup) personal communication, 13.6.2013).

Downthrow of the Hackness Rock Member seen on opposite sides of the fault seen 12.02.13 at -1.5 m depth (upthrow) and on 24.04.13 at -17 m depth (downthrow) gives an approximate throw of 15.5 m to the east.

6.3.5 -20 m OD: 14/05/2013

The fault was observed during the final shaft visit, but at this depth the displacement was between lower Osgody Formation sandstone (Red Cliff Rock Member; upthrow) and slightly paler upper Osgodby Formation sandstone (Langdale Member; downthrow). Strong saline water flow was again observed along the fault plane.

7 Sedimentology, stratigraphy and structural geology of the Toll House site in its regional context

7.1 SEDIMENTOLOGY

The Callovian to Oxfordian succession proved in the shaft and site investigation boreholes has provided significant new scientific data that help to better understand the sedimentary processes and their response to sea-level and tectonics during the Mid- to Late Jurassic (Wright. 1968;1977; Powell, 2010). These studies enable this important succession to be seen in the context of the wider deposition in the Cleveland Basin and offers parallels with Callovian-Oxfordian sedimentation in the North Sea, especially the broadly coeval Forties Field (Howard, 1985; Taylor and Gawthorpe, 1993; Gowland, 1996).

7.1.1 Bathonian (Scalby Formation;Long Nab Member)

Although the Lower Callovaian Cornbrash Formation and underlying Bathonian Scalby Formation were not seen in the shaft excavations, which terminated above this stratigraphical level, they were proved in Boreholes 1-3-03C and 1-3-04 (Figure 4). In the latter borehole the Long Nab Member of the Scalby Formation is represented by pale grey, leached sandstone overlying very light grey mudstone with sparse carbonaceous plant fragments. Sphaerosideite is present in mudstone lower in the sequence, which is attributed, along with the leached structureless nature of the sandstone, as indicative of pedogenetically altered (humic) floodplain sediments deposited on a low-gradient alluvial plain (Leeder and Nami, 1979; Riding and Wright, 1989; Romano and Whyte, in Scrutton and Powell, 2006; Powell, 2010).

A greater thickness of the Scalby Formation (Long Nab Member) was proved in BH 1-7-10 and BH 2-7-10 on the north-west side of Castle Hill, where these floodplain sandstones and mudstones show a typical ‘saw-tooth’ gamma-ray profile (Figure 26) the upper part of which is seen in BH 1-3-04 at Toll House. The distinctive gamma-ray low seen at ca. 50m depth below the base of the Cornbrash Formation in BH 1-7-10 is probably the Moor Grit Member (sandstone) at the base of the Scalby Formation.

7.1.2 Early Callovian (Cornbrash and Cayton Bay formations)

The global sea-level rise during the Herveyi Zone (Early Callovian) is marked by the disconformable, locally erosional, boundary at the base of the Cornbrash Formation. In the boreholes the boundary is irregular over a few centimetres, indicating erosional scouring of the Scalby floodplain during the initial transgression (Figure 10). This contracts with a boundary at outcrop in Cayton Bay where downward penetrating *Thalassinoides* (crustacean) burrows pipe coarser burrow-fill into soft Scalby mudstones, indicating that the underlying sediments were soft or firm i.e. unlithified during the marine transgression (Wright, 1968; Powell, 2010). Although the Cornbrash Formation core is generally fractured, there are sufficient fragments to allow the palaeoenvironment to be established. Iron-rich, sandy limestone was deposited in shallow water lagoons, with the generation of berthierine ooids in oscillating tidal conditions on adjacent highs. Encrusting oysters (*Lopha; Ostrea*) and other bivalves thrived, and are often preserved *in-situ,* along with brachiopods and serpulid worms. Free-swimming (nektonic) ammonites, belemnites and calcareous foraminfera were preserved on the sea-floor, but sedimentation rates were low, allowing burrowing organisms such as crustaceans and worms to modify the primary sedimentary structures. Subsequently, during late diagenesis much of the iron silicate and iron carbonate was altered to ferroan calcite.

The Cornbrash Formation marks a major rise in sea-level in early Callovian times (Herveyi Zone) (Figure 27), about 164.7 Ma (Gradstein et al., 2012). This marine transgression marks a major sequence boundary and marine flooding surface across the pre-existing, low-gradient alluvial plain represented by the underlying Scalby Formation. The presence of abundant shallow-water bivalves including encrusting oysters, together with free-swimming ammonites and belemnites suggest a shallow marine, upper shoreface environment. Abundant berthierine (chamosite) ooids dispersed throughout the limestone and the high bioturbation index (Taylor et al., 2003) point to slow rates of sedimentation.

The Cayton Bay Formation is poorly represented in the borehole cores at Toll House, possibly due to core loss or re-drilling. Elsewhere in the region, for instance at Cayton Bay, it is up to 3 m thick and was assumed to be about this thick near Castle Hill and North Bay (Wright, 1968; fig. 5). However, no great thickness is seen in the gamma-ray logs, and the boreholes record, at most, 0.25 m of dark grey, laminated siltstone and mudstone with grey, fine-grained sandstone laminae.

The formation is interpreted as representing the maximum flooding of the Early Callovian transgression. Dark grey, laminated mud and fine sand, and the absence of encrusting oysters, burrows, and berthierine ooids in this thin unit indicate deposition in deeper water than the underlying Cornbrash Formation.

7.1.2.1 RED CLIFF ROCK MEMBER

Ripple cross-lamination and thin pale grey sand laminae in the lowermost part of the Osgodby Formation indicates a shallowing environment as medium-grained sand was distributed offshore during storm events. These primary sedimentary structures are, however, uncommon, as most of the sand/silt sediment has been bioturbated by a variety of burrowing organisms (Figure 12). Relic sedimentary lamination is occasionally seen as sand-dominated and mud-dominated units ca. 0.05 m thick (Figure 12). Burrow traces are marked by pale grey relatively clean sand (burrow-fill) surrounded by zones and laminae of organic-rich sand (burrow wall). There is a greater concentration of black pyrite ooids in the organic-rich laminae compared to the clean sand fraction (burrow-fill), suggesting a concentration and sorting of the pyrite ooids during the backfilling of the burrows. Between 33.85 and 33.65 m depth in BH 1-3-03C pale grey siderite nodules with dispersed pyrite ooids and *Rhizocorallium* and *Teichichnus* burrows suggests slower sedimentation rates and longer residence time on the sea floor. This level, at about 5 m above the base of the formation, may be equivalent to the coarser sandstone unit and overlying β2 unit illustrated for the Castle Hill section by Wright (1968, figure 5) although that figure shows these beds about 7 to 8 m above the base. In BH1-3-04 a distinctive white, fine-grained orthoquatzite bed (0.10 m thick @ 2.18 m above the base) has thin horizontal laminae with small pyrite ooids and ripple cross-lamination at the base. This represents rapidly deposited storm sand with a highly mobile substrate that prevented colonisation by the ubiquitous burrowing organisms.

Pyrite ooids have not been previously described from this formation, although berthierine ooids were noted by previous authors (Wright, 1968; 1977; Page, in Cox and Sumbler, 2002.) It is not certain if the mineralogy of the ooids has been misidentified in hand specimen by previous workers, since all the black ooids in the cores are pyritic. Pyrite ooids have concentric laminae, often, initiated around a quartz grain (Figure 13). Individual lamina are thicker than those seen in the berthierine ooids of the Cornbrash Fm. and Hackness Rock Mbr., and are composed of small pyrite clusters or framboids (Figures 13 and 14). The outer cortex is often abraded or squeezed between adjacent surrounding quartz grains suggesting the ooids were relatively soft and deformable at the time of deposition. Sulphidic iron-rich mud, the precursor sediment of the ooids requires anoxic/reducing conditions to form, an environment very different from the oxygenated, storm-deposited, quartz-rich sands indicated by the lower Osgodby Formation. An explanation for the concentric nature of the pyrite ooids may be through the mechanism of a fluctuating redox interface in response to the availability of organic carbon within anoxic muds (Pufahl and Grimm, 2003). Such redox-aggregated pyrite ooids do not require mechanical rolling on the sea-floor as with carbonate ooids. Pufahl and Grimm (2003) propose a mechanism whereby concentric cortex of iron sulphide (composed of individual pyrite framboids) are built around a grain, in situ, as the redox interface shifts up and down in response to biological oxygen demand and the flux of organic carbon at the sediment-water interface. The origin of the pyrite ooids in the Osgodby Formation is uncertain, but it is hypothesised that they developed in anoxic (reducing) conditions in shallow, anoxic muddy lagoons where there was abundant availability of organic matter (amorphous plant debris), in the nearshore coastal zone; ooids were subsequently dispersed off shore along with quartz sand by during storm-surge events. This would account for the anomalous association of pyrite ooids in oxygenated sandy sediment, and would also explain the abraded nature of the outer cortex (Figure 14).

Sparse, stunted and thin-shelled bivalves and occasional belemnite guards in this member indicate highly mobile substrates that were inimical to bottom-dwelling shelly faunas, but the high proportion of amorphous organic matter favoured rapid colonisation by sediment ingesting ichnofauna.

7.1.2.2 LANGDALE MEMBER

The boundary between this unit and the underlying Red Cliff Rock Member is highly gradational, and is tentatively taken at a gradational upward decrease in grain-size from 31.20 m to 29.00 m in BH1-3-03C. Above this level the Langdale Member (upper part of the Osgodby sandstone) is generally fine-grained, paler grey in colour, and is characterised by a lower proportion of amorphous organic matter. Pyrite ooids are uncommon. The upward increase in the proportion of vertically orientated burrows in the Langdale Member indicates a response of bottom-dwelling infauna to more frequent episodes of erosion and deposition, which caused organisms such as crustacea, bivalves and worms to move up and/or down in the sandy substrate in response to local scouring, erosion and deposition. Belemnite guards and thin-shelled bivalves are occasionally present. The uppermost 5 m are more intensively burrowed with consecutive burrowing events illustrated as tier structures (Howard, 1985; Gowland, 1996; Taylor et al, 2003) with first arrival of the *Chondrites* organism, followed by *Teichichnus*, *Siphonites* and *Diplocraterion* or *Rhizocorallium.* The lower proportion of amorphous organic matter and absence of pyrite ooids compared to the Redcliff Rock Member suggests rising sea-level and blanketing of the forested coastal plain (hinterland) that provided abundant organic matter to the lower Osgodby sands. The carbonate content (cement) increases upward, and thin laminae with thin-shelled bivalves, brachiopods and wood fragments (drifted logs) are present in the uppermost metre.

7.1.2.3 HACKNESS ROCK MEMBER

The boundary between the Langdale and Hackness Rock members is gradational, but is generally marked by a shell bed (Figure 17) above which the carbonate content, proportion of berthierine ooids, and shelly fossils in the sandstone increases over an interval of about 0.30 m. This upward-shallowing trend marks a regressive event through the late Athleta Zone and Lamberti Zones, a result of a global sea-level fall (Cox and Sumbler, 2002; Gradstein et al., 2010). In BH 2-3-01 the basal shell bed has a scoured, erosive base with bivalve escape structures above, followed by common *Diplocraterion* and *Rhizocorallium* burrows suggesting a storm shell-lag deposit followed by colonisation of the substrate during waning current flow. This is overlain by bioturbated, berthierine-ooid rich, sandy limestone with abundant bivalves (e.g. *Gryphaea*, *Ostrea*), sparse brachiopods and serpulid worms, ammonites and belemnites (Figure 17). Clusters of *Gryphaea* bivalves were seen *in situ* in the shaft excavation (Figure 23). Berthierine ooids are often less concentrated in pale grey burrow-fill (e.g. *Planolites, Thalassinoides, Teichichnus*) indicating post-depositional sorting of the sediment (Figures 18,19).

The Hackness Rock Member represents a condensed sequence deposited in the near-shore zone, probably the upper shoreface, during a period of rising sea-level in the Late Callovian. This transgressive event cut off siliciclastic sediment supply, resulting in condensation of the sandy carbonate sediment. In contrast to the pyrite ooids seen in the lower Osgodby Formation, berthierine ooids were formed in oscillating tidal conditions on local highs and re-deposited in shallow depressions on the sea-floor (Williams, 2002)

7.1.3 Oxfordian (Oxford Clay Formation;Weymouth Member)

The boundary between the Osgodby Formation and the Oxford Clay Formation is rarely seen at outcrop. It marks the Callovian (Lamberti Zone) - Lower Oxfordian (Mariae Zone) boundary at around 163.5 Ma (Gradstein et al., 2012). In core, the boundary is sharp and the lowermost 0.15 m to 0.25 m of the Oxford Clay Formation is a grey and brownish grey siltstone with poorly contrasted burrow-mottling, oysters and wood fragments and dispersed small berthierine ooids (Figure 20). The latter are interpreted as being reworked from the underlying Hackness Rock sands, but the presence of *Planolites*, *Chondrites*, *Siphonites and Ophiomorpha* burrows suggests a lower shoreface setting during the initial marine transgression. An interesting feature in the basal 0.06 m in BH 1-3-02 and 2-3-01 is the presence of contorted, convolute laminae, possibly a result of rapid dewatering during the initial transgressive event. The proportion of berthierine ooids decrease upwards (only rarely present 0.20 m above the base). Nektonic fauna represented by thin-shelled ammonites and belemnites indicates deeper-water conditions above the bioturbated base. Drifted wood fragment suggest a proximity to the shoreline. About 2 m above the base there is a gradual change to light grey, blocky textured calcareous siltstone, but lacking depositional laminae. However, *Pinna* bivalves are preserved *in-situ* in the core and shaft. These siltstones have abundant, small diameter pyrite-filled burrows that form curved traces parallel to bedding (Figure 21) probably produced by worms feeding just below the sediment-water interface.

The lower Oxford Clay succession records a major global rise in sea-level in Mariae Zone times that blanketed much of the shallow-marine shoreface and lagoonal environments represented by the Hackness Rock Member. The presence of the warm water Tethyan dinoflagellate *Scriniodinium crystallinum* (Figure 28) may indicate global warming and thermal expansion of the Tethys Ocean, which resulted in marine flooding of the Callovian shelf environments (Riding, 2012)

7.1.4 Regional context

The depositional environments of the Bathonian to Lower Oxfordian succession proved in the Toll House boreholes and shaft, outlined above, are summarised in Figures 276 and 29. The lower, middle and upper shoreface environments represented by the Osgodby Formation show strong similarities with the Fulmar Formation of the Central North Sea Graben (Johnson *et al*., 1986), especially the Lower Fulmar Member (Donovan et al., 1993; Gowland, 1996). In the Central Graben of the North Sea the Lower Fulmar Member is very similar to the Osgodby Formation; shallow marine sandstones pass laterally to deeper water marine mudstones and turbidite lenses. Its base overlies fluviatile mudstones and sandstones (Pentland Formation) similar to the Scalby Formation onshore. Although the Cornbrash Formation is not described offshore, the Early Callovian marine transgression is marked by marine sandstones. Significantly, the internal lithofacies associations and trace fossil assemblages of the Lower Fulmar Member (Gowland, 1996) are similar to those seen in the Toll House boreholes and shaft. Gowland’s Facies Association D interpreted as representing ‘Distal lower shoreface/proximal offshore transition’ is similar to the lower Osgodby Formation (Red Cliff Rock Member) which passes upwards to Facies Association C representing ‘Bioturbated lower shoreface’ seen onshore in the overlying Langdale Member. The condensed berthierine ooidal sequence (Hackness Rock Member) is not represented in the Lower Fulmar Member offshore, presumably because of greater tectonically induced subsidence rates in the Central Graben, but some lithofacies elements onshore are similar to the Facies Association C (bioturbated lower shoreface) especially the presence of granule/pebble lags, shell coquinas (including thick shelled oysters), and deep-tier reworking by *Ophiomorpha* (crustacean) burrows. In the Central Graben the transition from shallow marine sandstone to marine mudstone (c.f. Osgodby Fm. to Oxford Clay Fm.) is diachronous, younging westwards, through the Oxfordian Stage in comparison to the Mariae Zone event seen onshore.

Consequently, the curated Callovian to Oxfordian core represented by the Toll House boreholes provides a useful analogue for studies of this interval in the Fulmar Field (North Sea).

7.2 LITHOSTRATIGRAPHICAL QUESTIONS

Although the formal lithostratigraphy of the succession proved in the Toll House boreholes can be broadly matched to the standard scheme (Wright, 1968, 1977; Page, 1989; Rawson and Wright, 2000; Cox and Sumbler, 2002) there remain some doubts about the recognition of the Red Cliff Rock Member and the overlying Langdale Member (Figure 9). The boundary between these members at Castle Hill, as shown in Figure 5 of Wright (1968), is based largely on Huddleston’s 1886 account, especially the lower part of the section where an upward coarsening marked by medium-grained sandstone and ammonites (ca. 4.3 m tick in total) is shown at the top of the Kellaways (Red Cliff) Rock Member; this trend continues in the medium-grained sandstone (ca.1.5 m thick) at the base of the Langdale Member. These beds could not be identified in the Toll House cores and shaft where the boundary between these two members is highly gradational over an interval of about 2.5 m of bioturbated sandstone. Indeed the Red Cliff Rock and Langdale members appear to record a continuum of storm-generated, bioturbated, distal to lower and middle shoreface sedimentation throughout Callovian time (c.f. Lower Fulmar Formation), rather than the standard scheme of sand-dominated units separated by a marked depositonal hiatuses comprising approximately three ammonites zones (late Koenigi to early Coronatum zones), which must represent at time gap of millions of years (compare Figures 9 and 27).

A possible explanation for the coarser grained sandstone with ammonites figured in these previously exposed beds on the foreshore near Toll House is that these beds actually represent Hackness Rock Member on the downthrow side of the newly identified Toll House Fault, which were misinterpreted in Victorian times. The ca. 15 m throw to the east on this fault would, indeed, displace the Hackness Rock Member, as seen in the outcrop at South Toll House cliff, approximately 15 m to the foreshore immediately to the east. If correct, there may be implications for the ammonite zonal stratigraphy in this area as Fox-Strangways (1892) and Arkell (1930) both remarked that many of the ammonite specimens in museums were collected from fallen or loose blocks and an attempt was made to locate their stratigraphical level by matching the lithology of the surrounding matrix with the outcrop.

7.3 BIOSTRATIGRAPHY

7.3.1 Micropalaeontology

7.3.1.1 SUMMARY

The composite succession cored and sampled in this study generally produced productive palynomorph associations which are indicative of the Bathonian–Callovian transition to the earliest Oxfordian interval. Although the stratigraphical precision in the Callovian is not at the resolution of the standard (ammonite) zonation, the palynofloras and the palynofacies are consistent with a relatively continuous succession throughout the Cornbrash, Cayton Clay and Osgodby formations. The **Long Nab Member (Scalby Formation)** yielded a sparse marine palynoflora, which is consistent with the Bathonian–Callovian transition. The overlying **Cornbrash Formation** is characterised by relatively diverse dinoflagellate cyst floras which unequivocally indicate an Early Callovian age. The **Cayton Clay Formation** and the oldest two units of the **Osgodby Formation**, the **Red Cliff Rock** and **Langdale Beds** members, yielded similar organic residues. These are extremely rich in amorphous organic matter and relatively sparse, low diversity dinoflagellate cyst floras. The high levels of amorphous organic matter are consistent with oxygen-poor bottom waters. The dinoflagellate cyst assemblages are indicative of an Early–Middle Callovian age for this succession. The Langdale Beds Member produced more diverse dinoflagellate cyst floras, and this strongly suggests that this unit is of Middle Callovian age. There is no palynological evidence of significant hiatuses below and above the Langdale Beds Member. The Hackness Rock Member of the Osgodby Formation is of Late Callovian age due to the presence of index dinoflagellate cysts such as *Trichodinium scarburghensis* and *Wanaea thysanota*. The Oxford Clay Formation is of earliest Oxfordian age (Mariae Zone) due to the occurrences of dinoflagellate cyst taxa such as *Gonyaulacysta dentata,* and *Wanaea fimbriata.*

7.3.1.2 LONG NAB MEMBER (SCALBY FORMATION)

Three samples were examined from the Long Nab Member from boreholes 1-3-03C and 1-3-04. They yielded relatively sparse, low diversity palynofloras, especially those from borehole 1-3-

04. This is consistent with the findings of Riding and Wright (1989). The sample at 41.68 m in borehole 1-3-03C produced the marine dinoflagellate cysts *Ctenidodinium combazii*, *Impletosphaeridium varispinosum, Meiourogonyaulax caytonensis* and *Pareodinia ceratophora*. The range of *Impletosphaeridium varispinosum* is latest Bathonian to Early Callovian (Riding, 1987; Riding and Thomas, 1992), hence this horizon is latest Bathonian to Early Callovian in age. The presence of *Ctenidodinium combazii* and *Meiourogonyaulax caytonensis* is consistent with this interpretation.

7.3.1.3 CORNBRASH FORMATION

The Cornbrash Formation (formerly the Cornbrash Limestone) was sampled in boreholes 1-3-03C and 1-3-04. The samples typically produced relatively abundant palynofloras including prominent dinoflagellate cysts. This reflects the change from the paralic sedimentation in the underlying Ravenscar Group (Scalby Formation) to the open marine conditions of the Callovian. The dinoflagellate cysts comprise *Ctenidodinium combazii*, *Ctenidodinium continuum*, *Gonyaulacysta jurassica* subsp. *adecta, Impletosphaeridium varispinosum, Korystocysta gochtii, Meiourogonyaulax caytonensis, Mendicodinium groenlandicum, Nannoceratopsis pellucida, Pareodinia ceratophora, Pareodinia halosa, Pareodinia prolongata*, *Rhynchodiniopsis cladophora, Rigaudella aemula, Sirmiodinium grossii* and *Tubotuberella dangeardii*. This association is consistent with floras previously reported from the Cornbrash Formation (e.g. Sarjeant, 1959; Riding, 1987), and the occurrence of marine microplankton is consistent with an open marine depositional scenario.

The dinoflagellate cyst assemblages are indicative of a Callovian age (Riding, 1992; 2005). More specifically, the range bases of, for example, *Rhynchodiniopsis cladophora* and *Rigaudella aemula* are of earliest Callovian age (Riding and Thomas, 1992). The range tops of *Ctenidodinium combazii* and *Impletosphaeridium varispinosum* are Early Callovian, within the Calloviense Zone (Riding and Thomas, 1992; Riding, 2005; unpublished data). This confirms the Early Callovian age of the Cornbrash Formation.

7.3.1.4 CAYTON CLAY FORMATION

One sample was collected from the Cayton Clay Formation (formerly 'Shales of the Cornbrash'), this is at 33.85 m from borehole 1-3-04. This sample was dominated by amorphous organic matter and proved relatively sparse in palynomorphs. The abundance of amorphous organic matter is indicative of oxygen depletion at the sediment-water interface. The palynoflora largely comprises pollen grains such as *Callialasporites* spp. and *Classopollis classoides*. Only a single specimen of the dinoflagellate cyst *Rhynchodiniopsis cladophora* was encountered. This occurrence is consistent with a Callovian age (Riding, 1992).

7.3.1.5 RED CLIFF ROCK MEMBER (OSGODBY FORMATION)

This unit was only sampled in borehole 1-3-03C between 40.80 m and 35.23 m. The three samples produced organic residues extremely rich in amorphous organic material; palynomorphs are sparse. The dinoflagellate cysts recognised include? Gonyaulacysta *jurassica* subsp. *adecta,* indeterminate forms, *Korystocysta gochtii,* ?*Meiourogonyaulax* spp., *Mendicodinium groenlandicum, Valensiella ovulum* and *Valensiella* spp. The presence of these forms is consistent with significant marine input. This sparse, low diversity dinoflagellate cyst association does not include any biostratigraphically-significant forms. However, it is characteristic of the Callovian, and would be consistent with an Early–Middle Callovian age (Riding, 2005).

7.3.1.6 LANGDALE MEMBER (OSGODBY FORMATION)

This unit is typified by extremely high levels of amorphous organic material, and relatively sparse palynomorph associations. The dinoflagellate cyst assemblages are of moderate diversity, and normally comprised forms such as *Chytroeisphaeridia chytroeides, Ctenidodinium continuum*, *Ctenidodinium ornatum, Escharisphaeridia* spp., *Fromea tornatilis, Gonyaulacysta jurassica* subsp. *adecta, Korystocysta gochtii, Korystocysta pachyderma, Nanoceratopsis pellucida*, *Meiourogonyaulax planoseptata, Meiourogonyaulax* spp., *Mendicodinium groenlandicum, Pareodinia* spp., *Rhynchodiniopsis cladophora, Sentusidinium* spp., *Surculosphaeridium vesitum, Tubotuberella dangeardii, Valensiella* spp. and *Wanaea acollaris.* These forms are consistent with a fully marine palaeoenvironment.

This assemblage, particularly *Gonyaulacysta jurassica* subsp. *adecta, Korystocysta* spp., *Nanoceratopsis pellucida*, *Meiourogonyaulax* spp., *Mendicodinium groenlandicum* and *Wanaea acollaris,* is typical of the Callovian (Riding, 2005). The presence of *Ctenidodinium continuum, Ctenidodinium ornatum* and *Rhynchodiniopsis cladophora* means that this unit is of definite Callovian age (Riding, 1992). No Early or Late Callovian markers such as *Ctenidodinium combazii* and *Wanaea thysanota* respectively were recorded; this, and the higher dinoflagellate cyst diversity, strongly suggests a Middle Callovian age for the Langdale Beds Member. *Meiourogonyaulax planoseptata* was recorded in sample 41, from the middle part of the Langdale Beds Member in borehole 2-3-1. This species is characteristic of the Early Callovian of eastern England (Riding, 1987), but is known from younger strata in Russia (Riding et al., 1999). In summary therefore, the Langdale Beds Member is interpreted as being of probable Middle Callovian age. However, there is no palynological evidence for this unit being entirely confined the Middle Callovian Coronatum Zone (Cope et al., 1980, fig. 8; Cox and Sumbler, 2002, fig. 5.2). Furthermore, the palynomorphs and palynofacies do not indicate the presence of significant hiatuses below and above the Langdale Beds Member.

7.3.1.7 HACKNESS ROCK MEMBER (OSGODBY FORMATION)

The Hackness Rock Member generally produced productive palynomorph associations. These include relatively abundant and diverse dinoflagellate cyst assemblages which is consistent with an open marine depositional setting. These floras include *Ambonosphaera*? *staffinensis*, *Chytroeisphaeridia* spp., *Ctenidodinium continuum*, *Ctenidodinium ornatum*, *Endoscrinium galeritum, Escharisphaeridia* spp., *Fromea tornatilis, Gonyaulacysta jurassica* subsp. *adecta, Korystocysta* spp., *Meiourogonyaulax* spp., *Mendicodinium groenlandicum, Pareodinia* spp., *Prolixosphaeridium* spp., *Rhynchodiniopsis cladophora, Sentusidinium* spp., *Sirmiodiniopsis orbis, Sirmiodinium grossii, Stephanelytron redcliffense, Surculosphaeridium vesitum, Trichodinium scarburghensis, Tubotuberella dangeardii* and *Wanaea thysanota.* These associations are comparable with existing reports of latest Callovian dinoflagellate cysts from northwest Europe (e.g., Riding, 1982; Berger, 1986; Prauss, 1989; Riding and Thomas, 1997).

The overlapping ranges of *Ctenidodinium continuum, Trichodinium scarburghensis* and *Wanaea thysanota* are indicative of a Late Callovian age. The inceptions of *Trichodinium scarburghensis* and *Wanaea thysanota* lie in the Athleta Zone, and the range top of *Ctenidodinium continuum* is close to the Callovian-Oxfordian transition (Woollam, 1980; Riding and Thomas, 1992). No Oxfordian index taxa are present. *Mendicodinium groenlandicum* is especially common in sample 38 (borehole 2-3-1, 21.50 m). An acme of this species is characteristic of the latest Callovian Lamberti Zone (Riding and Thomas, 1997).

The key sample is number 21 (borehole 1-3-02, 14.00 m), which yielded *Trichodinium scarburghensis* and *Wanaea thysanota*.

7.3.1.8 OXFORD CLAY FORMATION

The Oxford Clay Formation yielded relatively abundant and diverse palynoforas, which are consistently rich in marine forms. This indicates an open marine depositional setting for this unit. The dinoflagellate cyst floras include prominent *Gonyaulacysta jurassica* subsp. *adecta, Rhynchodiniopsis cladophora, Sentusidinium* spp., *Surculospharidium vesitum* and *Trichodinium scarburghensis*. Other forms recorded include *Chytroeisphaeridia* spp., *Compositosphaeridium polonicum, Endoscrinium galeritum, Gonyaulacysta dentata, Gonyaulacysta eisenackii, Gonyaulacysta jurassica* subsp. *adecta* var. *longicornis* (large morphotype), *Gonyaulacysta jurassica* subsp. *jurassica, Meiourogonyaulax* spp., *Mendicodinium groenlandicum, Nannoceratopsis pellucida, Pareodinia* spp., *Prolixosphaeridium* spp., *Scriniodinium crystallinum, Sirmiodinium grossii, Tubotuberella dangeardii, Wanaea fimbriata* and *Wanaea thysanota*. This assemblage compares well to other records of Early Oxfordian marine microplankton from Europe (e.g., Woollam, 1980; Riding and Thomas, 1997; Riding, 2005).

Certain key dinoflagellate cyst taxa are indicative of an earliest Oxfordian age (Mariae Zone). Specifically, the presence throughout of *Gonyaulacysta jurassica* subsp. *jurassica* means that this unit can be no older than the earliest Oxfordian, because the range base of this subspecies is in the Mariae Zone (Riding and Thomas, 1992). The range top of *Gonyaulacysta dentata* is also within the Mariae Zone; this report represents the first record of the boreal species *Gonyaulacysta dentata* from England (Riding, 2012). *Wanaea fimbriata* is confined to the Early Oxfordian. Moreover, the presence of *Gonyaulacysta jurassica* subsp. *adecta* var. *longicornis* (large morphotype), *Scriniodinium crystallinum* and *Wanaea thysanota* are extremely characteristic of the Early Oxfordian (Riding and Thomas, 1997).

The key samples are number 35 (borehole 2-3-1, 20.46 m) which yielded *Gonyaulacysta dentata*, and numbers 19 (borehole 1-3-02, 10.00 m) and 34 (borehole 2-3-1, 15.2 m), which include *Wanaea fimbriata.*

7.3.2 Macropalaeontology

7.3.2.1 SUMMARY

Macrofossils were obtained from the split core, including levels above the curated, slabbed core shown in Appendix 1. Additional specimens were collected at the excavated shaft levels. Much of the material is fragmentary, but the following results indicate the presence of the major ammonite zones and in some case the subzones for the Hackness Rock Member (Osgodby Formation) and the Oxford Clay Formation. The lower two members of the Osgodby Formation the Cayton Clay Formation and Cornbrash Formation did not yield diagnostic ammonites.

7.3.2.2 HACKNESS ROCK MEMBER (OSGODBY FORMATION)

Quenstedoceras cf. *lamberti* (J. Sowerby) was found at - 3.0 m OD in the shaft and the *Kosmoceras* [M] fragment at - 17 m OD suggest respectively the Lamberti and Athleta zones.

7.3.2.3 OXFORD CLAY

Cardioceras cf. *scarburgense* (Young & Bird) at 11.25 m depth and *Quenstedoceras* cf. *mariae* (d'Orbigny) at 11.34 m in Borehole 1-3-03C indicate the Mariae Zone, Scarburgense Subzone.

Relatively abundant *Peltoceras* specimens were seen particularly well in Borehole 2-3-1 between 15.10 m and 18.10 m are the Lower Oxfordian forms often referred to *Parawedekindia* *arduennense*. Page (1991) assigned them instead to species of *Peltoceras (Peltomorphites)* such as *subtense* (Bean) and *hoplophorus* (Buckman). On the Yorkshire coast (e.g. at Cornelian Bay and Red Cliff), they have been recorded from the Mariae Zone, Praecordatum Subzone but, although they appear to occur at a higher stratigraphical level than the ammonites noted above in Borehole 1-3-03C, without accompanying cardioceratids in Borehole 2-3-1 and more detailed assessment of records elsewhere, subzonal assignment is here left open.

Macrofossil of determinations for the boreholes and shaft are listed in Appendices 2 and 3.

7.4 STRUCTURAL GEOLOGY

As noted in Section 6.1, the Castle Hill outlier is bounded to the west by major extensional normal faults interpreted as part of the onshore-offshore Peak Fault system (Milsom and Rawson, 1989; Rawson and Wright, 2000, figure 2). The new Toll House Fault, trending approximately 350 º N and downthrowing ca. 15.5 m east is an important discovery that helps our interpretation of the geological structure of the area (Figure 26). The eastward plunge of the shallow Castle Hill syncline (Figures 1 and 30) is probably due to easterly fault drag on the Toll House Fault. Furthermore, the new fault explains the anomalously high structural dip seen in the extant Hackness Rock Member outcrop at South Toll Hose Cliff (Figure 2), again a result of local fault drag related to this fault. At -17 m OD in the shaft the dip increased up to 20 º towards 110 º N, within the Osgodby Formation (footwall side) (Figure 25), in close proximity to the fault. Calcite and pyrite mineralisation along fractures adjacent to the fault suggest an ancient movement possibly related to the Tertiary 'Alpine' orogeny (Hemingway and Ridler, 1982). Fault drag, at approximately right angles to the fault trace suggests dip-slip (normal) faulting rather than strike-slip displacement. Offshore from the Yorkshire coast, Milsom and Rawson (1989) showed that fault movement within the Peak Trough occurred from Triassic through to Tertiary times; there may have been synsedimentary Jurassic movement on the Toll House Fault, but this was not proven in this study. The Toll House Fault is interpreted as a splay fault branching off the main Castle Hill Fault, the latter marking the western bounding fault of the Peak Trough; the eastern bounding fault is represented by the Red Cliff Fault (downthrow west) that is seen in Cayton Bay and which then trends NNW offshore from Castle Hill (Powell and Reay, 1982).

The geomorphology of Castle Hill is also controlled to some extent by the Toll House Fault. The Castle Hill outlier forms a promontory chiefly as a result of the hard, resistant nature of the Corallian Group (sandy limestones) cap-rock downfaulted against the less resistant Ravenscar Group rocks (mudstones and poorly cemented sandstones). However, the Toll House Fault must have controlled the eastern cliff edge during sea-level rise during the late Quaternary to Holocene; the harder Hackness Rock Member would have been exposed on the downthrow (seawards) side of the lower cliff and foreshore, thereby protecting the Castle Hill promontory from marine erosion during rising sea-levels.

8 Conclusions

- Study of the site investigation boreholes cores, gamma-ray logs and shaft geology has provided a wealth of new information on the Callovian-Lower Oxfordian succession, only part of which is exposed in the South Toll House Cliff geological Site of Special Scientific Interest (SSSI).
- The value of the geological findings is both of scientific and historical-scientific value, because the lower part of the succession investigated by pioneering Victorian geologists

on the lower foreshore has not been visible since the construction of Marine Drive (1897-1907) and more recent rock-armouring of the foreshore.

- The full Lower Oxfordian to Lower Callovian succession was proved in boreholes represented, in downward sequence, by the lower part of the Lower Oxfordian Oxford Clay Formation (Weymouth Member); Callovian Osgodby Formation, including the Hackness Rock, Langdale and Red Cliff Rock members; the Early Callovian Cayton Bay and Cornbrash formations, and the uppermost Bathonian Scalby Formation.
- The upper part of the Lower Oxfordian to Lower Callovian succession, down to the level of the Red Cliff Rock Formation, was proven in the Toll House shaft excavation to -20 m OD depth.
- The Osgodby Formation is interpreted as a bioturbated lower to upper shoreface, silty sandstone similar in lithofacies to the Lower Fulmar Member of the Central Graben, North Sea. It overlies a condensed transgressive marine unit, the Cornbrash Formation and the attenuated Cayton Clay Formation. This Early Callovian marine transgression flooded the low gradient alluvial plain represented by the underlying Scalby Formation (Long Nab Member).
- The presence of latest Bathonian to Early Callovian palynofloras in the uppermost Scalby Formation indicates that there was no great time gap between the deposition of this paralic unit and the overlying marine Cornbrash Formation (also Early Callovian in age).
- Condensed sequences, deposited during marine transgressions, rich in berthierine (iron silicate) ooids and abundant shelly fossils including oysters, ammonites and belemnites, are represented by the Cornbrash Formation and Hackness Rock Member at the base and top of the Callovian succession, respectively. The intervening Osgodby Formation sandstone (Red Cliff Rock and Langdale members) is extensively bioturbated with virtual destruction of primary sedimentary structures by a diverse ichnofauna (trace fossil) assemblage that scavenged the sandy substrate rich in amorphous organic matter. Sedimentation rates were slow, with long sediment residence time on the sea-floor resulting in a high bioturbation index.
- Newly recorded pyrite ooids in the lower Osgodby Formation sandstones are interpreted as being formed in anoxic lagoons in the nearshore zone as a result of a fluctuating redox interface; ooids were subsequently swept offshore during storm surge-ebb events to be deposited on the lower shoreface along with bi-modal quartz sand.
- Warm water dinoflagellates of Tethyan Ocean affinity *(Scriniodinium crystallinum)* in the lower part of the Oxford Clay Formation indicate a Lower Oxfordian age, confirmed by the presence of the zonal ammonite species *Quenstedoceras mariae* in the lowermost siltstone. Warm water dinoflagellates may indicate thermal warming and ocean water expansion during Mariae Zone time that led to a global sea-level rise and widespread marine transgression.
- Shaft excavations revealed a new major fault, the Toll House Fault, trending ca. 350 ºN, downthrowing the Hackness Rock Member about 15.5 m to the east. The fault appears to control the eastern side of Castle Hill and is responsible for the anomalously high dip in the South Toll House Cliff SSSI due to local fault drag. The Toll House Fault is interpreted to be a splay fault branching off the main Castle Hill Fault, which together form the western bounding faults of the Peak Trough that extends northwards, offshore. Faulting along Marine Drive, parallel to the cliff may explain some of the anomalies between the stratigraphy seen in the borehole cores compared to those reconstructed from Victorian records of the formerly exposed lower cliff and foreshore.

9 Recommendations

1. In addition to the Toll House site investigation cores that form part of this study, the wider site investigation borehole cores drilled from the top of Castle Hill and adjacent fault blocks to the west represent a scientifically valuable record of the Middle Oxfordian to Bathonian succession i.e. from the Coralline Oolite Formation (Hambleton Oolite Member) down to the Scalby Formation, and possibly the upper part of the Scraborough Formation (Ravenscar Group). We recommend that these cores are donated to BGS as part of the curated archive at the National Geological Repository, Keyworth, Nottingham.
2. The current study demonstrates the value of a multidisciplinary geological approach, and the additional value of collaboration between BGS, major utility companies, and civil engineering schemes in recording, updating and curating geological information for the nation. In addition to its scientific value, such information helps to upgrade the national geological base map/model, and offers information for future researchers and civil engineering schemes. Although the Toll Hose site has special significance in respect of its SSSI status, we recommend that other major civil engineering infrastructure schemes develop collaborative studies with BGS.

Appendix 1 Toll House boreholes: core photographs

Appendix figure 1. Borehole 1-3-03C core: 4.40 – 10.00 m.

Appendix figure 2. Borehole 1-3-03C core: 10.00- 14.00 m

Appendix figure 3. Borehole 1-3-03C core: 14.00- 18.00 m

Appendix figure 4. Borehole 1-3-03C core: 19.00-23.00 m

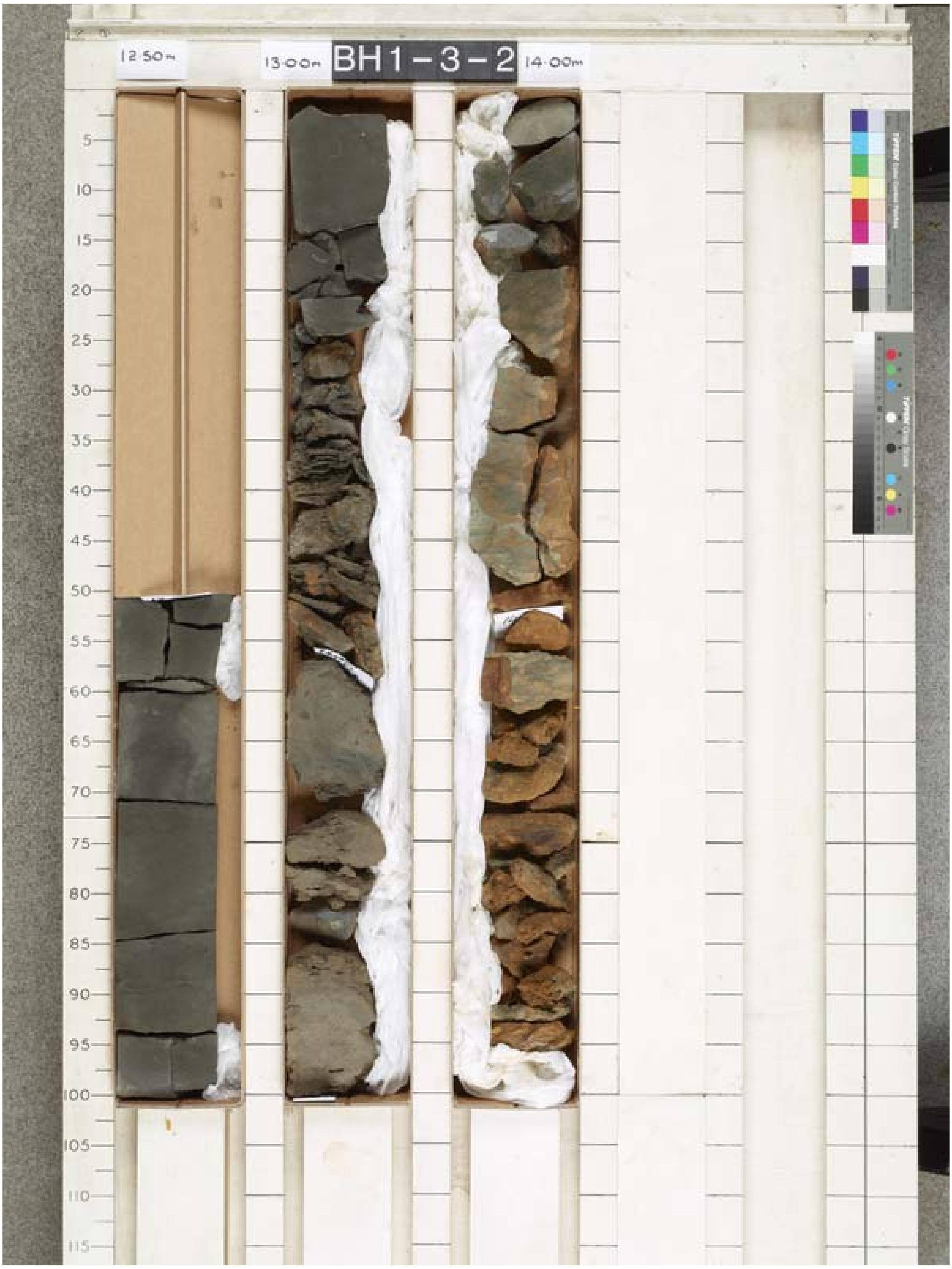
Appendix figure 5. Borehole 1-3-03C core: 23.00 – 27.00 m

Appendix figure 6. Borehole 1-3-03C core: 27.00- 31.00 m

Appendix figure 7. Borehole 1-3-03C core: 31.00- 35.00 m

Appendix figure 8. Borehole 1-3-03C core: 35.00- 38.00 m

Appendix figure 9. Borehole 1-3-03C core: 39.00- 41.70m

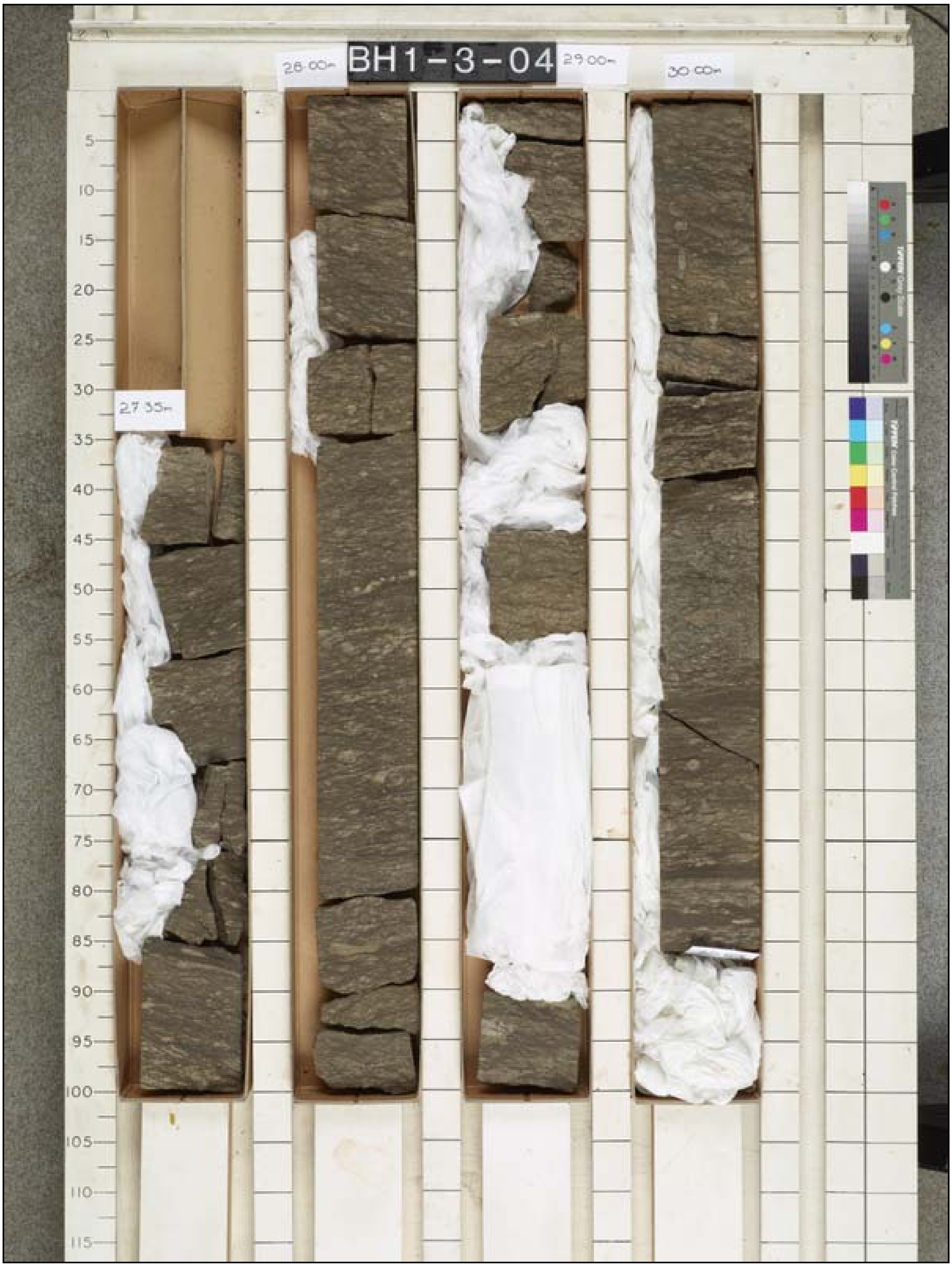


Appendix figure 10. BoreholeBH1-3-2 core: 12.50 – 15.00 m

Appendix figure 11. Borehole BH1-3-2 core: 15.00-17.50 m

Appendix figure 12. Borehole BH 2-3-1 core: 17.50-21.00 m

Appendix figure 13. Borehole BH 2-3-1 core: 21.00-25.00 m



Appendix figure 14. Borehole BH1-3-04 core: 27.35-31.00.00 m

Appendix figure 15. Borehole BH1-3-04 core: 31.00– 34.00 m

Appendix figure 16. Borehole BH1-3-04 core: 34.00-36.00 m

Appendix 2 Macrofossil identifications from the Toll House shaft

Notes: Depths below ordnance datum (OD); Numbers refer to JHP samples numbers.

-1.5 m OD

Oxford Clay Formation

27. *Peltoceras* sp. fragment

28. Slender pyritized trails + ammonite fragments including cardioceratid

29. ?*Peltoceras* fragment

Hackness Rock Member

18. ?*Peltoceras* whorl fragment

19. *Chlamys* and indeterminate ammonite

20. *Cylindroteuthis*

21. *Quenstedtoceras* fragment cf. *lamberti* (J. Sowerby)

22. *Quenstedtoceras sp.* and fragment

25. Wood fragment + ? *Quenstedtoceras* [M] body chamber fragment

- 3.0 m OD

Oxford Clay Formation

9. Ammonite fragment (?*Hecticoceras*)

Hackness Rock Member

10. *Quenstedtoceras* cf. *lamberti* (J. Sowerby)

11. *Gryphaea lituola* (Lamarck), ?*Cylindroteuthis*, ? pectinid juv., perisphinctid ammonite (?*Grossouvria* sensu Page 1991).

12. *Gryphaea lituola* (Lamarck)

13. Shell fragments, clusters of rhynchonellids, wood fragment

14. Bivalves and shell fragments including *Gryphaea*, rhynchonellids, belemnite

Langdale Member

15. Wood fragment + indeterminate shell fragments including bivalves

- 14 m OD

Oxford Clay Formation: 5 specimens including *Peltoceras* [M] sp. fragment

Osgodby Formation (fault downthrow): 6 specimens including burrows and wood fragment

- 17 m OD

Osgodby Formation: 2 specimens with burrows

Hackness Rock Member (fault downthrow): 15 specimens including *Kosmoceras* [M] fragment, bivalve and rhynchonellid fragments, *Gryphaea*, burrows, pyrite nuggets, calcite crystals (fault)

- 20 m OD

Osgodby Formation: 5 specimens with extensive burrows and burrow-mottling, belemnite fragment.

Appendix 3 List of macropalaeontological specimens from the Toll House Boreholes.

Notes: indet. = indeterminate; * = best preserved ammonites; inc. = including; (depths below ordnance datum)

Numbers refer to JHP samples numbers.

Borehole No. BH 1-3-03C	Macro-Pal. Sample No.	Macro-Pal. Sample Depth (m)	Notes
Oxford ClayFormation (Weymouth Member)	1	9.38	Ammonite fragment, indet, pyritised perisphinctid
	2	9.43	Ammonite fragment, indet.
	3	9.44	Burrow
	4	10.02	Ammonite heel fragment
	5	11.05	Ammonite fragment, pectinid bivalves and burrows (pyritized)
	6	11.10	Bivalve fragments, indet; *Gryphaea* juv.
	7	11.25	*Ammonite: *Cardioceras scarburgense* (Young & Bird)
	8	11.27	Faecal pellets
	9	11.30	Faecal pellets and ooids (berthierine?)
	10	11.32	Faecal pellets and ooids
	11	11.34	*Ammonite: *Quenstedtoceras mariae* (d'Orbigny)
	12	11.45	Faecal pellets/ooids
Osgodby Fm (Hackness Rock Mbr.)	13	11.72	Ammonites: cardioceratid fragment & ?*Hibolithes* belemnite; (Hackness Rock)
	14	11.95	Various shelly fossils inc. rhynchonellid brachiopods; ?*Oxytoma* ammonite; wood fragments
	15	11.97	Belemnite indet.
Langdale Member (?)	16	12.80	*Diplocraterion* and *Teichichnus* burrows
	17	14.50	Rhynchonellid brachiopod; wood fragments
	18	19.30	Small thin-shelled bivalves; juvenile ?*Meleagrinella*
	19	22.20	*Chondrites* burrows
	20	23.30	Belemnite indet.
Red Cliff Rock Member ('Kellaways Rock')	21	25.40	Bivalve fragment
	22	25.80	*Ophiomorpha* pellet-lined burrow
	23	28.30	Belemnite fragment
	24	29.30	Belemnite fragment
	25	31.10	Belemnite fragment
	26	33.80	Shell fragments including rhynchonellid brachiopods

(contd.) Red Cliff Rock Member ('Kellaways Rock')	27	33.85	Fragments and juvenile bivalves inc. *Meleagrinella* and oyster.
	28	35.09	Concretion with small shell fragments
	29	39.75	Bivalve fragments
Cornbrash Formation	30	41.00	Bivalve fragments and *Lopha*
	31	41.70	Thin shelled bivalves including *Entolium* and *Pleuromya*.

Borehole No. BH 1-3-02	Macro-Pal. Sample No	Macro-Pal. SampleDepth (m)	Notes
Oxford Clay (Weymouth Member)	1	9.30	Pyritised burrows
	2	11.45	Ammonite: ?*Peltoceras* impression; burrows
	3	11.47	Shelly fragments including ammonites; *Peltoceras*
	4	12.05	Burrow
	5	12.60	Bivalve/ammonite fragments, *Peltoceras*
	6	12.95	Bivalve fragments including *Pinna*
	7	13.10	Pyritised, bifurcating burrows
	8	13.20	Ammonite and bivalve fragments inc. *Lopha*
Osgodby Fm. (Hackness Rock Member)	9	14.30	Bivalve fragment: ?*Radulopecten scarburgensis* (Young & Bird)
	10	15.43	Rhynchonellid brachiopod and oysters fragments
	11	15.60	*Gryphaea* shell bed with rhynchonellids
	12	15.62	Bivalve fragments including ?*Gryphaea* and *Meleagrinella*

Borehole No. BH 1-3-04	Macro-Pal. Sample No.	Macro-Pal. Sample Depth (m)	Notes
Red Cliff Rock Member ('Kellaways Rock')	1	27.40	Bivalve fragments inc. ?*Lopha*
	2	27.80	Rhynchonellid brachiopods
	3	28.08	Bivalve fragments inc. *Meleagrinella*
	4	28.80	Bivalve; *Meleagrinella*
	5	29.91	Indet. bivalve fragments
	6	30.30	Bivalve fragments inc. ?*Lopha* and ?*Meleagrinella*
	7	30.85	Bivalve: *Meleagrinella*
	8	33.40	Bivalve fragments inc. ?*Lopha* and *Meleagrinella*
Cornbrash Formation	9	33.60	*Entolium corneolum* (Young & Bird) & oysters including ?*Lopha*
	10	33.45	Oysters inc. *Lopha, Entolium* and ?*Oxytoma*
	11	34.36	Shell fragments and oyster (?*Lopha*), serpulids, and ?*Entolium*

Borehole No. BH 2-3-1	Macro-Pal. Sample No	Macro-Pal. Sample Depth (m)	Notes
Oxford Clay (Weymouth Member)	1	11.45	Fish spine?
	2	14.60	Bivalve; pyriytised burrows/trails
	3	14.65	Burrows; ammonite fragment indet.
	4	14.80	Pyritised burrows and plant fragments
	5	15.00	Small perisphinctid ammonite frags. & burrows
	6	15.10	Ammonite: *Peltoceras,* inner whorls (*P. (Peltomorphites*) of Page, 1991)
	7	15.18	Perisphinctid ammonite fragment
	8	15.29	*Ophiomorpha* burrows
	9	15.30	Plant fragment. with 'barbs'
	10	15.60	*Ammonite: *Peltoceras (?P.(Peltomorphites*) of Page, 1991)
	11	15.67	Large ammonite fragment: *Peltoceras*
	12	15.90	Ammonite: *Peltoceras* and burrows
	13	16.05	Pyritised burrows with barbs & shell frags.
	14	16.60	*Pinna* bivalve
	15	17.35	*Ammonite - ? *Quenstedtoceras mariae*.
	16	17.38	*Pinna* bivalves
	17a	17.82	Ammonite: *Peltoceras*
	17b	17.90	*Ammonite: *Peltoceras*
	18a	18.10	Ammonite: *Peltoceras*
	18b	18.70	Ammonite: poorly preserved cardioceratid
Osgodby Formation (Hackness Rock Member)	19	20.55	Bivalves indet. and several *Chlamys* & ?*Pseudolimea*
	20	20.60	Serpulids and bivalve fragments & juveniles
	21	20.80	Bivalves indet; *Oxytoma* fragment and cardiid.
	22	21.10	Ammonite fragment indet.; bivalves inc. *Grypahea lituola* (Lamarck)
	23	21.60	Bivalve indet.
	24	22.15	Shell bed with common rhynchonellid brachiopods and other shell fragments.inc. oysters at base of Hackness Rock Mbr.

Peltoceras ?ex.gr. *subtense* (Bean) and *P*. (*Peltomorphites*) of Page (1991) = *Parawedekudia ardueonsis* of literature

Appendix 4 List of palynological samples from the Toll House Boreholes

Borehole No. BH 1-3-03C	Palynology Sample No.	Palynology Sample Depth (m)	Notes
Oxford Clay Formation	1	9.00	Near top of core
	2	9.86	Mid part of core
	3	10.20	Near base of fm.
	4	11.55	At base of fm.
Osgodby Formation (Hackness Rock Mbr.)	5	11.92	Near top of fm.
	6	12.96	Near base of mbr..
(Langdale Member)	7	13.06	Near top of mbr.
	8	22.92	Near base of mbr.
	9	27.50	Near base of mbr.
	10	31.20	Near base of mbr.
(Red Cliff Rock Member)	11	35.23	Mid part of mbr.
	12	39.74	Near base of mbr.
	13	40.80	At base of mbtr./fm.
Cornbrash Formation	14	41.10	Top of fm.
	15	41.25	Mid part of fm.
	16	41.50	Mid part of fm.
	17	41.55	Base of fm.
Scalby Formation (Long Nab Member)	18	41.68	Top of fm.

Borehole No. BH 1-3-02	Palynology Sample No.	Palynology Sample Depth (m)	Notes
Oxford Clay Formation	1	10.00	Near top of core
	2	13.20	Near base of fm.
Osgodby Formation (Hackness Rock Mbr.)	3	14.00	Near top of fm.
	4	14.75	Near base of fm.
(Langdale Member)	5	15.70	Near top of mbr.
	6	21.40	Near base of mbr.

Borehole No. BH 1-3-04	Palynology Sample No	Palynology Sample Depth (m)	Notes
Osgodby Formation (Red Cliff Rock Mbr.)	1	9.20	Near top of fm.
	2	26.40	Mid (dark) part of mbr.

	3	33.60	Near base (dark) part of mbr.
Cayton Clay Formation	4	33.85	
Cornbrash Formation	5	34.30	Limestone
	6	34.85	Base of fm.
Scalby Formation	7	35.10	Pale sandstone, top of fm.
(Long Nab Member)	8	39..30	Very dark, top of fm.

Borehole No. BH 2=-3-1	Playnology Sample No	Palynology Sample Depth (m)	Notes
Oxford Clay Formation	1	10.15	Near top of core
	2	15.20	Mid part of core
	3	20.46	Near base of fm.
Osgodby Formation (Hackness Rock Mbr.)	4	20.75	Near top of fm.
	5	21.33	Mid (dark) part of mbr.
	6	21.50	Near base of mbr.
	7	22.30	Base (shelly) part of mbr.
(Langdale Member)	8	23.32	Near top of mbr.
	9	35.75	Mid (woody) part of mbr.
	10	42.62	Near base of mbr. (TD)

Total palynological samples = 42

Appendix 5 List of petrological samples from the Toll House Boreholes

Borehole No. BH 1-3-03C	Petrological. Sample No.	Petrological. Sample Depth (m)	Notes
Oxford Clay Formation	9	10.65	Porosity impregnation
Osgodby Formation (Hackness Rock Mbr.)	8	12.15	Carbonate stain & porosity impregnation
(Langdale Member)	7	14.95	Porosity impregnation
	6	18.45	
	5	26.80	
Red Cliff Rock Member.	4	32.30	
	3	34.48	
	2	39.95	
Cornbrash Formation.	1	41.05	Carbonate stain & porosity impregnation

References

British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: http://geolib.bgs.ac.uk.

ARKELL, W. J. 1933. *The Jurassic system in Great Britain*. (Oxford: Clarendon Press).

ARKELL, W.J. 1945. The zones of the Upper Jurassic in Yorkshire. *Proceedings of the Yorkshire Geological Society*, 25, 339-359.

BERGER, J.-P. 1986. Dinoflagellates of the Callovian-Oxfordian boundary of the "Liesberg-Dorf" quarry (Berner Jura, Switzerland). *Neues Jahrbuch für Geologie und Paläontologie Abhandlungen*, 172, 331–355.

BRINKMANN, R. 1926. Über die sedimentare Abbildung epiogener Beuvegung sonie uber das Schichtungsproblem. *Nachrichten von der Gesellschaft der Wissenschaften zu Göttingen, Matheematisch-physikalische Klasse*, 1925, 199.

BRITISH GEOLOGICAL SURVEY 1998a. Whitby and Scalby. England and Wales Sheet 35 &44. Solid and Drift Geology. 1:50 000 Provisional Series. (Keyworth, Nottingham: British Geological Survey.)

BRITISH GEOLOGICAL SURVEY 1998b. Scarborough. England and Wales Sheet 54. Solid and Drift Geology. 1:50 000 Provisional Series. (Keyworth, Nottingham: British Geological Survey.)

BUCKMAN , S.S. 1909-1930. *Yorkshire type ammonites*, vols I, II, 1909-1919. Type ammonites, vols III-VII, 1919-1930. Printed privately, London.

BUCKMAN, S.S. 1913. The 'Kelloway Rock' of Scarborough. *Quarterly Journal of the Geological Society of London*, 69, 152-68.

COPE, J.C.W., DUFF, K.L., PARSONS. C.F., TORRENS, H.S., WIMBLEDON, WA. and WRIGHT, J.K. 1980. A correlation of Jurassic rocks in the BRITISH Isles. Part Two: Middle and Upper Jurassic. Geological Society of London Special Report, No. 15, 109 pp.

COX, B. M, 1988. English Callovian (Middle Jurassic) Perisphinctid Ammonites, Part 1, Monographs of the Palaeontological Society, N0.575 (part of Volume 140 for 1986), Palaeontographical Society, London.

COX, B. M., HUDSON, J. D. and MARTILL, D. M. 1993. Lithostratigraphic nomenclature of the Oxford Clay (Jurassic). *Proceedings of the Geologists' Association*, 103 [for 1992], 343-345.

COX, B. M. and SUMBLER, M. G. 2002. British Middle Jurassic Stratigraphy. Joint Nature Conservation Committee. *Geological Conservation Review Series,* 26.

DONOVAN, A.D., DJAKIC, A.W., IOANNIDES, N.S., GARFIELD, T.R. and JONES, C.R. 1993. Sequence stratigraphic control on the Middle and Upper Jurassic reservoir distribution within the UK Central North Sea. *In*: Parker, J.R. (ed.) *Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference* . The Geological Society, London, 251-269.

DOUGLAS, J.A. and ARKELL, W.J. 1932. The stratigraphical distribution of the Cornbrash: 2. The north-eastern area. *Quarterly Journal of the Geological Society of London*, 88, 112-70.

FOX-STRANGWAYS, C.1892. Jurassic rocks of Britain, Vols. 1 and 2, Yorkshire. *Memoir of the Geological Survey of Great Britain.*

FOX-STRANGWAYS, C. and BARROW, G. 1915. The geology of the country between Whitby and Scarborough. *Memoir of the Geological Survey of Great Britain (2nd edition).*

GOWLAND, A.S., 1996. Facies characteristics and depositional models.of highly bioturbated shallow marine siliciclastic strata: an.example from the Fulmar Formation (late Jurassic), UK Central.Graben. In: Hurst, A., et al. (Eds.), *Geology of the Humber Group: Central Graben and Moray Firth, UKCS*. Geological.Society Special Publications, vol. 114, pp. 185–214.

GRADSTEIN, F. M. OGG, J. G. SCHMITZ, M. AND OGG, G. 2012. *The Geologic Time Scale 2012*. Elsevier.

HEMINGWAY, J.E. and RIDDLER, G.P. 1982. Basin inversion in north Yorkshire. *Transactions of the Institute of Mining and Metallurgy*, Section B, 91, 175-186.

HOWARD, A.S. 1985. Ichnofacies and depositional environments of the Fulmar Formation (U. Jurassic) in the Gannet and Kittiwake fields, central North Sea, *Stratigraphy and Sedimentology Research Group, Report* No. CS24/85/10 for BGS Hydrocarbons (Offshore) Research Programme.pp.18 +figs. and plates

HUDDLESTON, W.H.1876. The Yorkshire Oolites. Part 2: The Middle Oolites . *Proceedings of the Geologists' Association*, 4, 353-410.

JOHNSON, H.D., MACKAY, T.A. and STEWART, D.J. 1986. The Fulmar Oil-field (Central North Sea): geological aspects of its discovery, appraisal and development. *Marine and Petroleum Geology*, 3, 99-125.

LECKENBY, J. 1859. On the Kelloway Rock of the Yorkshire Coast. *Quarterly Journal of the Geological Society of London*, 15, 4-15.

LEEDER, M.R. and NAMI, M. 1979. Sedimentary models for the non-marine Scalby Formation (Middle Jurassic) and the evidence for late Bajocian/Bathonian uplift of the Yorkshire Basin. *Proceedings of the Yorkshire Geological Society*, 42, 461-482.

MILSOM, J. and RAWSON, P. F. 1989. The Peak Trough – a major control on the geology of the North Yorkshire coast. *Geological Magazine*, 126, 699-705.

PAGE, K.N. 1989. A stratigraphic revision for the English Lower Callovian. *Proceedings of the Geologists' Association*, 100, 363-382.

PAGE, K N 1991. Ammonites. pp. 86-143 in *Fossils of the Oxford Clay*. Palaeontological Association Field Guide to Fossils: Number 4.

PHILLIPS, J. 1829-32. *Illustrations of the geology of Yorkshire, or a description of the strata and organic remains*. Part 1. The Yorkshire Coast. (York: privately printed).

POWELL, J H. 1980. Preliminary report on the geological structure and stratigraphy of the area offshore from Castle Hill and Scalby Ness. *Report to Babtie, Shaw & Morton, consultants to the Yorkshire Water Authority*.17pp

POWELL, J.H. 2010. Jurassic sedimentation in the Cleveland Basin: a review. *Proceedings of the Yorkshire Geological Society*, 58, 21-72.

POWELL, J H and REAY, D M. 1982. Preliminary interpretation report on the geological structure and stratigraphy of the area offshore from Castle Hill, Scarborough. *IGS Continental Shelf Division, Marine Geophysics Unit, Report* No. UC/026. 9pp.

PRAUSS, M. 1989. Dinozysten-stratigraphie und Palynofazies im Oberen Lias und Dogger von NW-Deutschland. *Palaeontographica Abteilung* B, 214, 1–124.

PUFAHL, P. K. and GRIMM, K.A. 2003. Coated phosphate grains: Proxy for physical, chemical and ecological changes in seawater. *Geology*, 31, 801-804.

RAWSON, P. F. and WRIGHT, J. K. 2000. *The Yorkshire Coast. Geologists' Association Guide No.34. 3rd Edition*. The Geologists' Association.

RIDING, J.B. 1982. Jurassic dinocysts from the Warboys Borehole, Cambridgeshire, England. *Journal of Micropalaeontology*, 1, 13–18.

RIDING, J.B. 1987. Dinoflagellate cyst stratigraphy of the Nettleton Bottom Borehole (Jurassic: Hettangian to Kimmeridgian), Lincolnshire, England. *Proceedings of the Yorkshire Geological Society*, 46, 231–266.

RIDING, J.B. 1992. On the age of the Upper Ostrea Member, Staffin Bay Formation (Middle Jurassic) of north-west Skye. *Scottish Journal of Geology*, 28, 155–158.

RIDING, J.B. 2005. Middle and Upper Jurassic (Callovian to Kimmeridgian) palynology of the onshore Moray Firth Basin, northeast Scotland. *Palynology*, 29, 87–142.

RIDING, J.B. AND THOMAS, J.E. 1992. Dinoflagellate cysts of the Jurassic System. In: Powell, A.J. (ed.). *A stratigraphic index of dinoflagellate cysts.* British Micropalaeontological Society Publications Series. Chapman and Hall, London, 7–97.

RIDING, J.B. AND THOMAS, J.E. 1997. Marine palynomorphs from the Staffin Bay and Staffin Shale formations (Middle–Upper Jurassic) of the Trotternish Peninsula, NW Skye. *Scottish Journal of Geology*, 33, 59–74.

RIDING, J.B. and WRIGHT, J.K. 1989. Palynostratigraphy of the Scalby Formation (Middle Jurassic) of the Cleveland Basin, north-east Yorkshire. *Proceedings of the Yorkshire Geological Society*, 47, 349-354.

RIDING, J.B., FEDOROVA, V.A. AND ILYINA, V.I. 1999. Jurassic and lowermost Cretaceous dinoflagellate cyst biostratigraphy of the Russian Platform and northern Siberia, Russia. *American Association of Stratigraphic Palynologists Contributions Series*, No. 36, 179 pp.

RIDING, J.B. 2012. The Jurassic dinoflagellate cyst *Gonyaulacysta dentata* (Raynaud 1978) Lentin &Vozzhennikova 1990 emend. nov.: An index species for the Late Callovian to earliest Oxfordian of the northern hemisphere. *Review of Palaeobotany and Palynology,* 176-177, 68–81.

SARJEANT, W.A.S. 1959. Microplankton from the Cornbrash of Yorkshire. *Geological Magazine*, 96, 329–346.

SCRUTTON, C.T. AND POWELL, J.H. 2006. *Yorkshire Rocks and Landscape* – A Field Guide (3rd Edition). Yorkshire Geological Society, pp. 224.

TAYLOR, A.M., and GAWTHORPE, R.L., 1993. Applications of sequence stratigraphy and trace fossil analysis to reservoir description: examples from the Jurassic of the North Sea. In: Parker, J.R. (Ed.), *Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference. Geological Society, London*, pp. 317–335.

TAYLOR, A.M, GOLDRING, R. and GOWLAND, S. 2003. Analysis and application of ichnofabrics. *Earth-Science Reviews*, 60, 227-259.

WHYTE, M.A. and ROMANO, M. 2006. Middle-Upper Jurassic sequence between Cayton Bay and Yons Nab. In: Scrutton, C.T. & Powell, J.H. (Eds.) 2006. Yorkshire Rocks and Landscapes - A Field Guide, 3rd Edition, *Yorkshire Geological Society*, pp. 174-182.

WILLIAMS, M.E. 2002. Lateral variation within a hiatal-condensed bed and the controls on the formation and occurrence of berthierine ooids: a case study from the Middle Jurassic of NE England, UK. *Geological Journal*, 37, 279-296.

WOOLLAM, R. 1980. Jurassic dinocysts from shallow marine deposits of the East Midlands, England. *Journal of the University of Sheffield Geological Society*, 7.5, 243–261.

WRIGHT, J.K. 1968. The stratigraphy of the Callovian Rocks between Newtondale and the Scarborough Coast, Yorkshire. *Proceedings of the Geologists' Association*, 79, 363-399.

WRIGHT, J.K. 1977. The Cornbrash Formation (Callovian) in North Yorkshire and Cleveland. *Proceedings of the Yorkshire Geological Society*, 41, 325-346.

WRIGHT, J.K. 1983. The Lower Oxfordian (Upper Jurassic) of North Yorkshire. *Proceedings of the Yorkshire Geological Society*, 44, 249-281.

WRIGHT , T. 1860. On the subdivisions of the Inferior Oolite in the south of England, compared with equivalent beds of that Formation on the Yokshire coast. *Quarterly Journal of the Geological Society of London*, 16, 1-48.

YOUNG, G. and BIRD, J. 1822. *A geological survey of the Yorkshire coast*. Clark, Whitby iv + 322 pp.

Figure 1. Oblique aerial photograph of Castle Hill showing the geology and major faults prior to shaft sinking. Original photograph courtesy of Peter Smith.

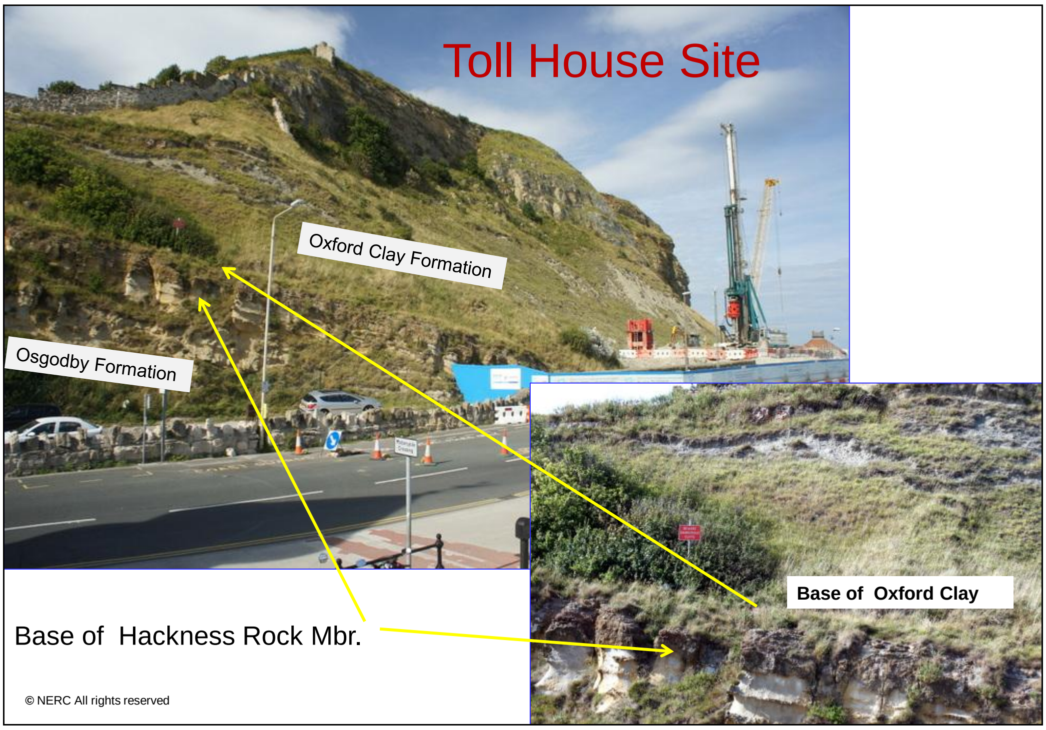


Figure 2. South Toll House Cliff showing local geology; note the high dip in the Osgodby Formation, a result of drag on the Toll House Fault. Photographs: J H Powell

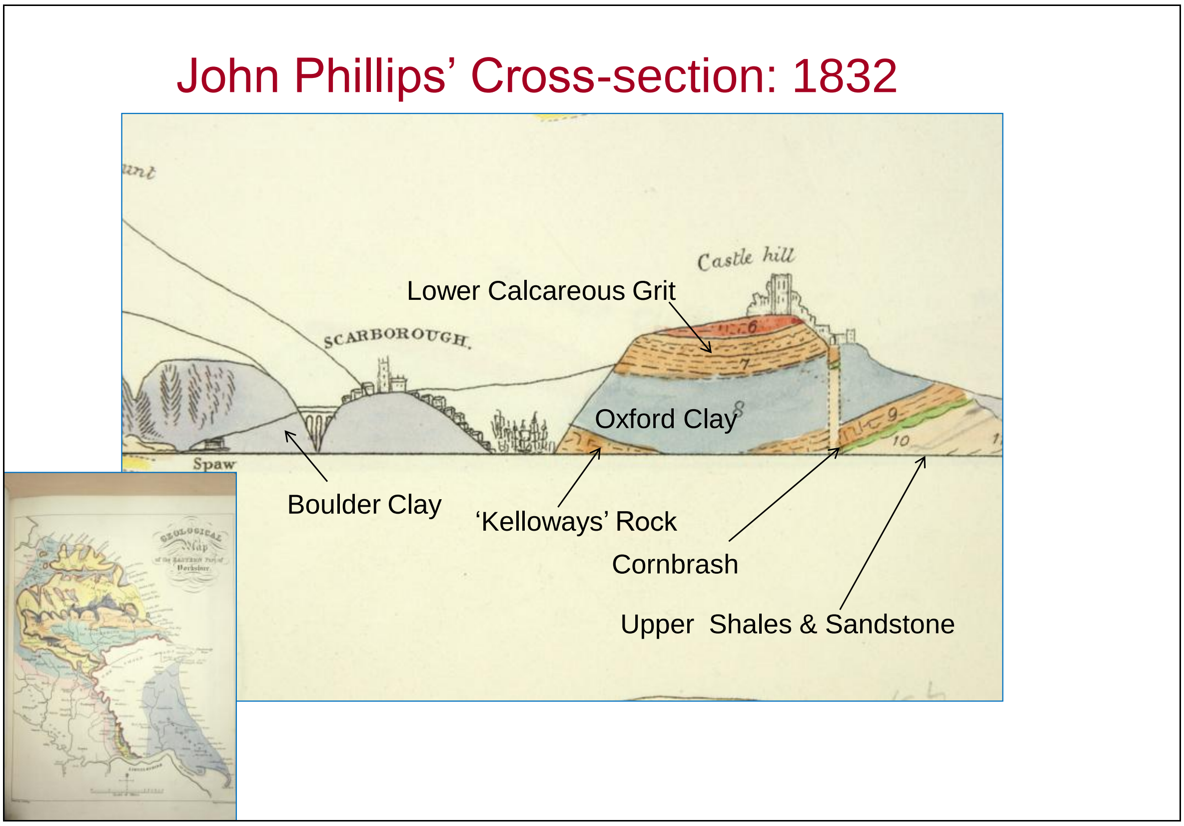


Figure 3. Excerpt from John Phillips' 1829-1832 book showing the cross-section of the Scarborough coast; inset is his accompanying geological map. Note Toll House site at arrow for 'Kelloways' Rock.

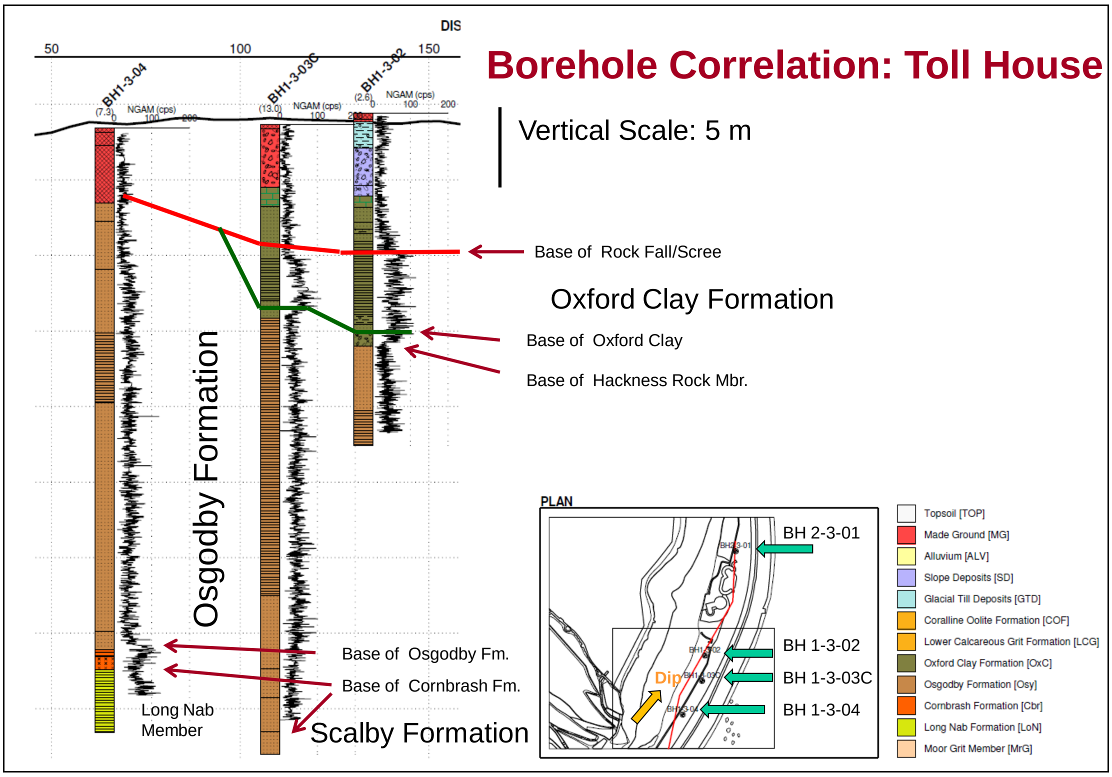


Figure 4. Summary site investigation logs and gamma-ray logs at Toll House, with re-interpreted lithostratigraphical boundaries based on core logging. Inset map shows the location of boreholes illustrated and BH 2-3-01. Base logs courtesy of Arup.

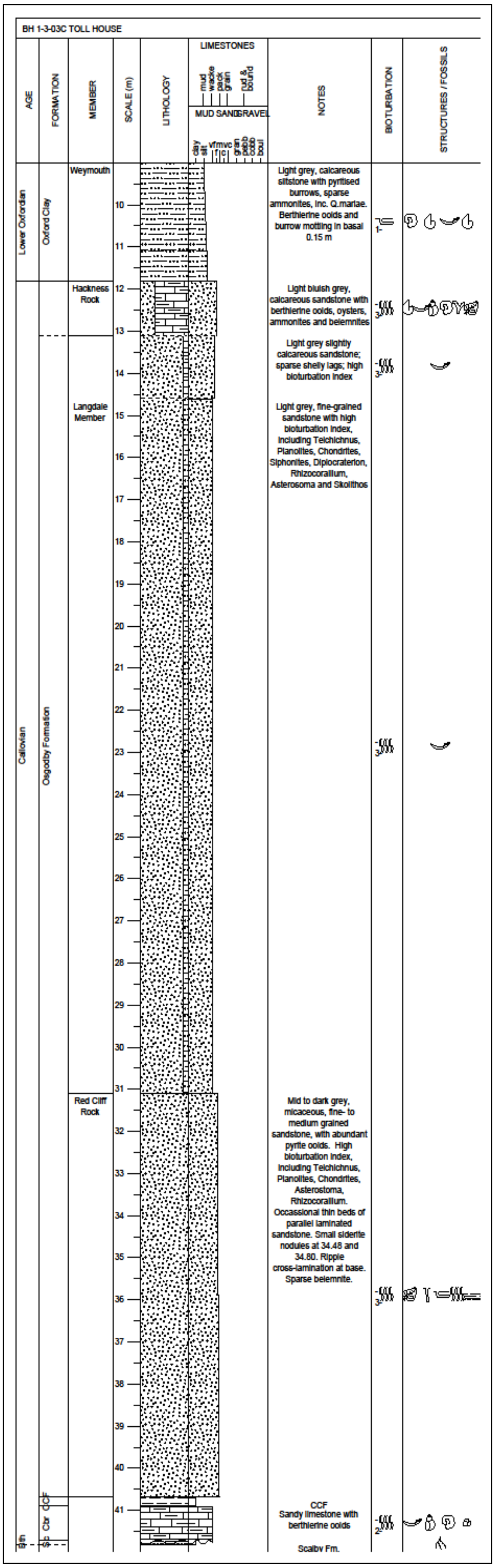


Figure 5. Graphic log of BH 1-3-03C. NGR: E [5]05209.71 N [4]88927.96

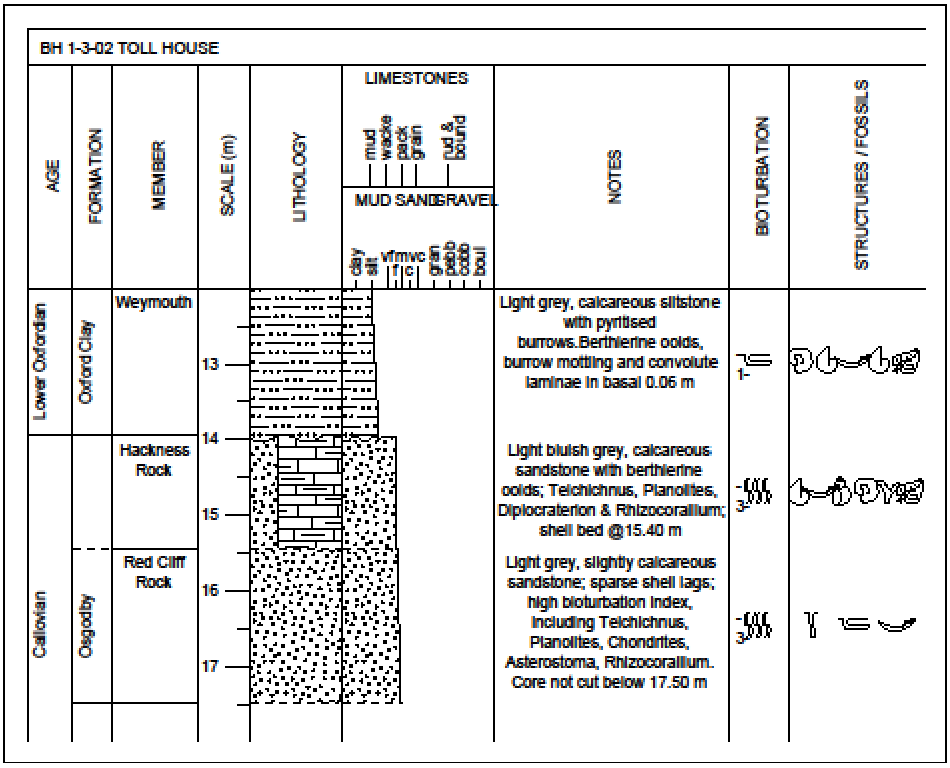


Figure 6. Graphic log of part of BH 1-3-02. NGR: E [5]05212.78 N [4]88954.57

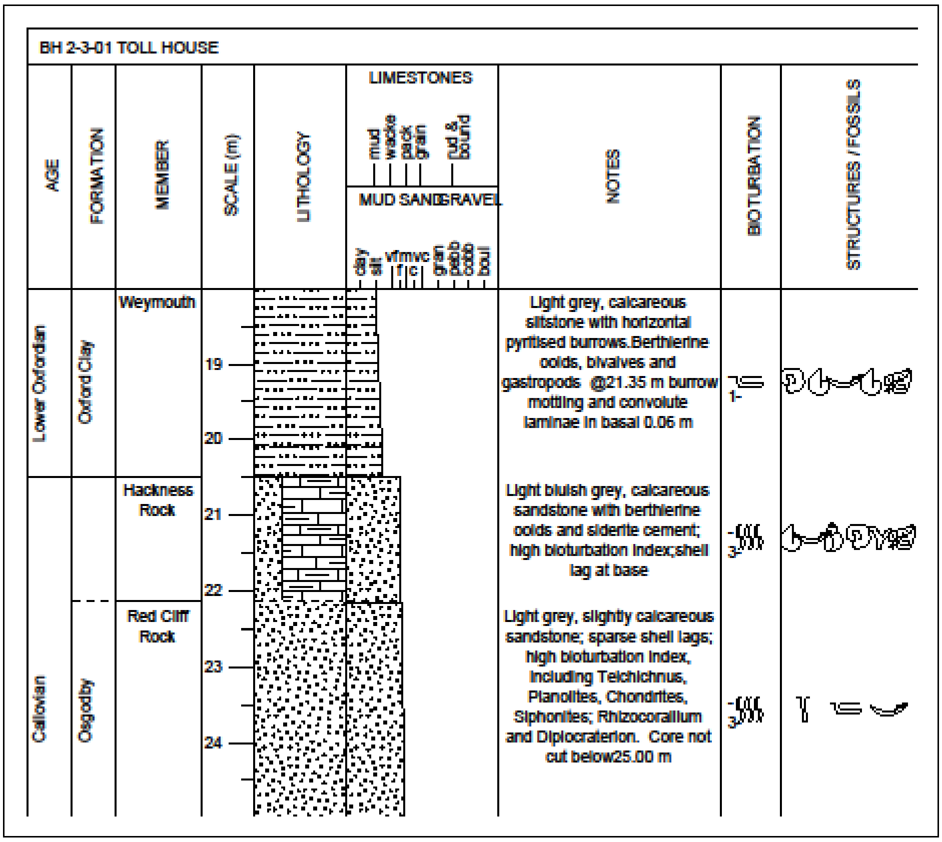


Figure 7. Graphic log of part of BH 2-3-01. NGR: E [5]05245.07 N [4]89064.11

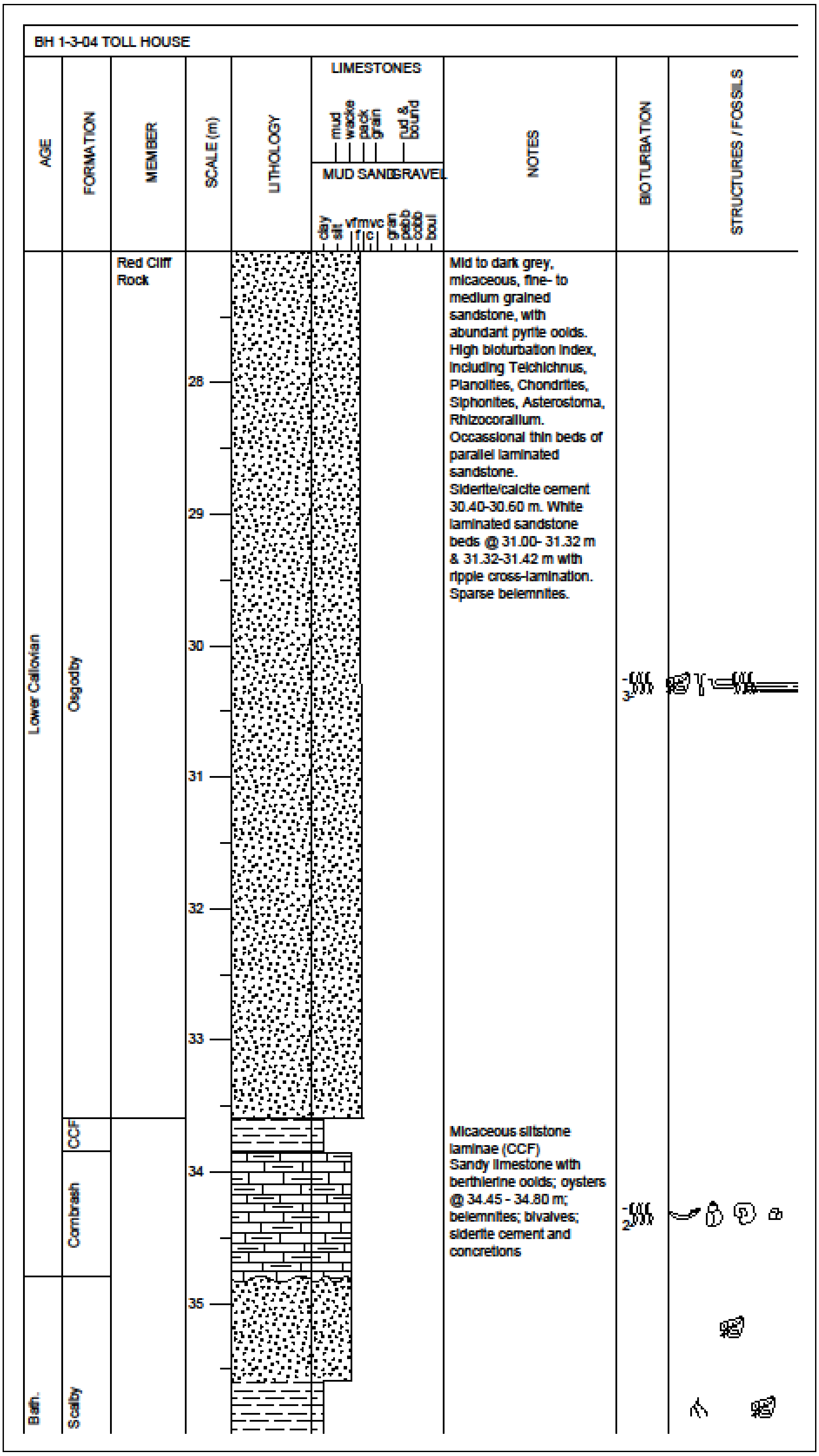


Figure 8. Graphic log part of BH 1-3-04. NGR: E [5]05189.35 N [4]88892.65

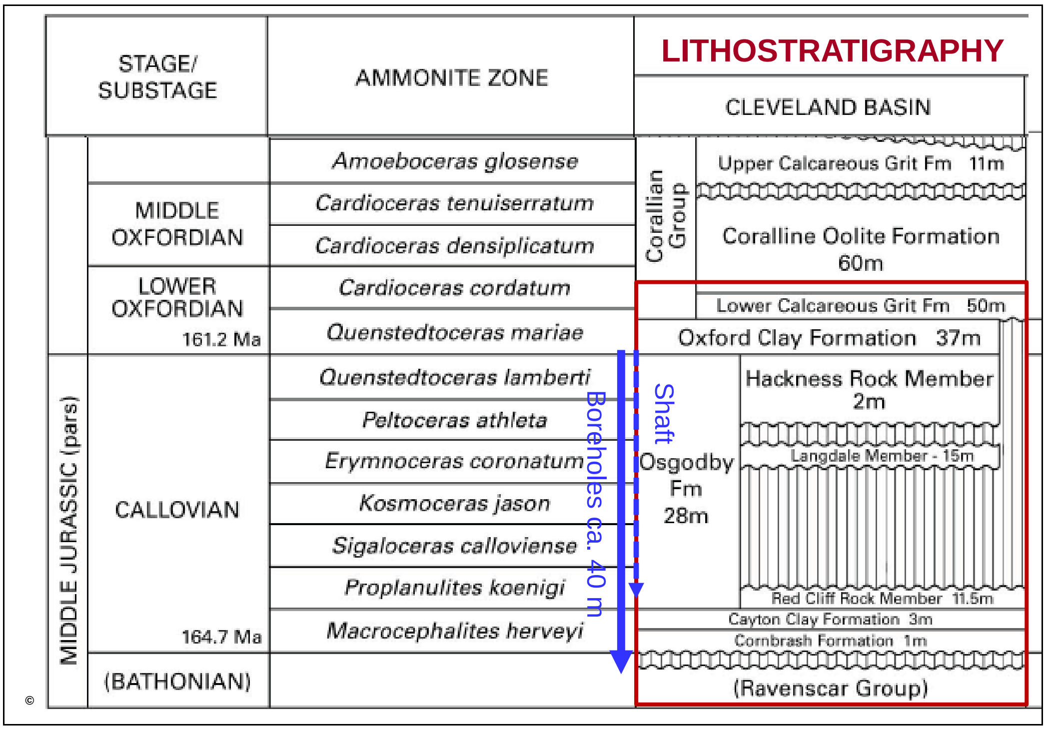


Figure 9. Biostratigraphical and lithostratigraphical scheme (after Rawson and Wright, 2000) for the succession seen in the Toll House boreholes (solid blue arrow) and shaft (dashed blue arrow).

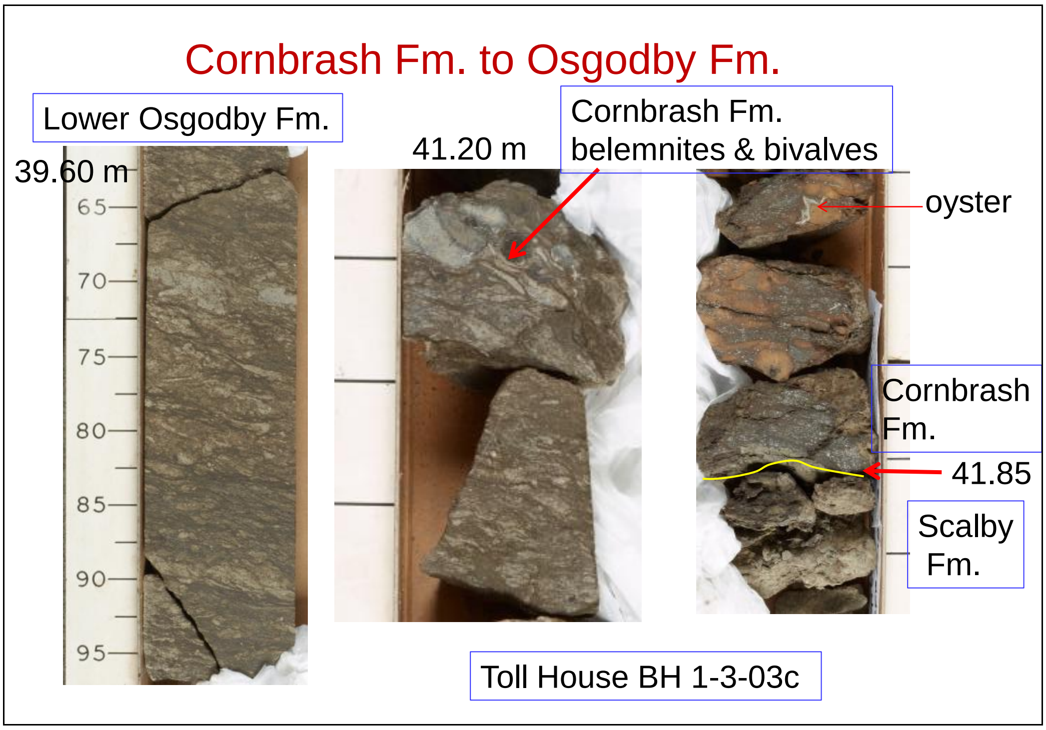


Figure 10. Core photographs (BH 1-3-03C) showing (right) berthierine ooidal sandy limestone (Cornbrash Formation) resting unconformably on Scaby Formation sandstone, shelly fossils and (left) lower Osgodby Formation with relic bedding mostly destroyed by burrowing organisms.

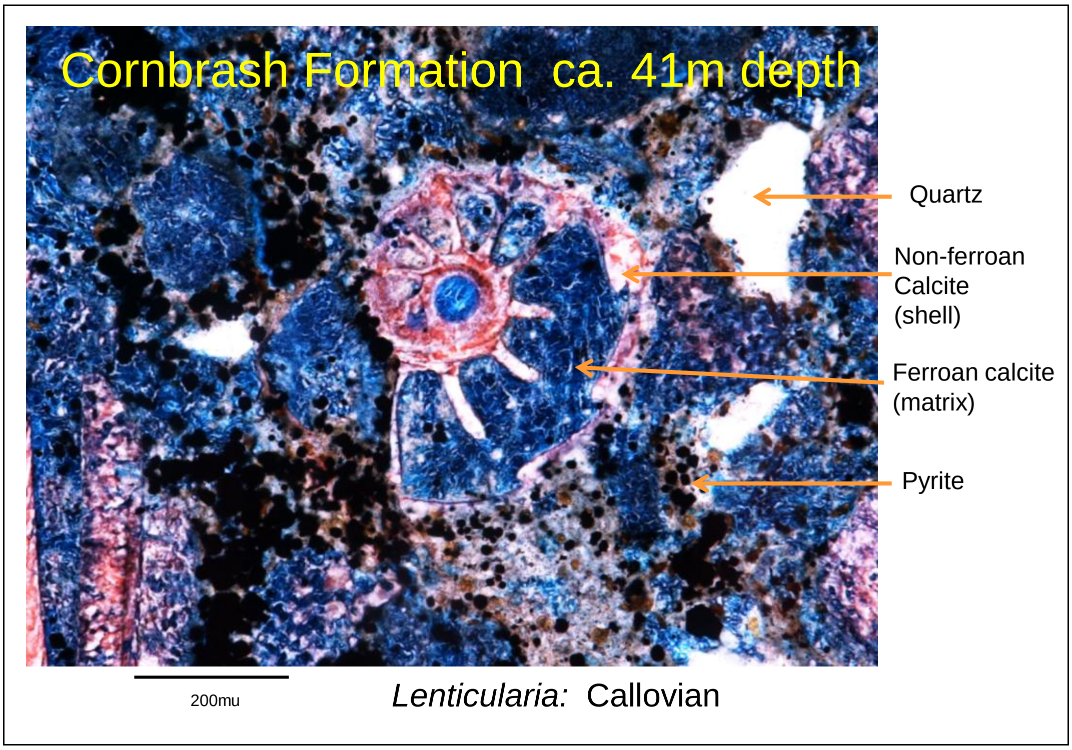


Figure 11. Carbonate stained photomicrograph of the Cornbrash Formation at 41 m depth in BH1-3-03C @ 41.05 m showing the foraminifera *Lenticularia* sp.and petrological features.

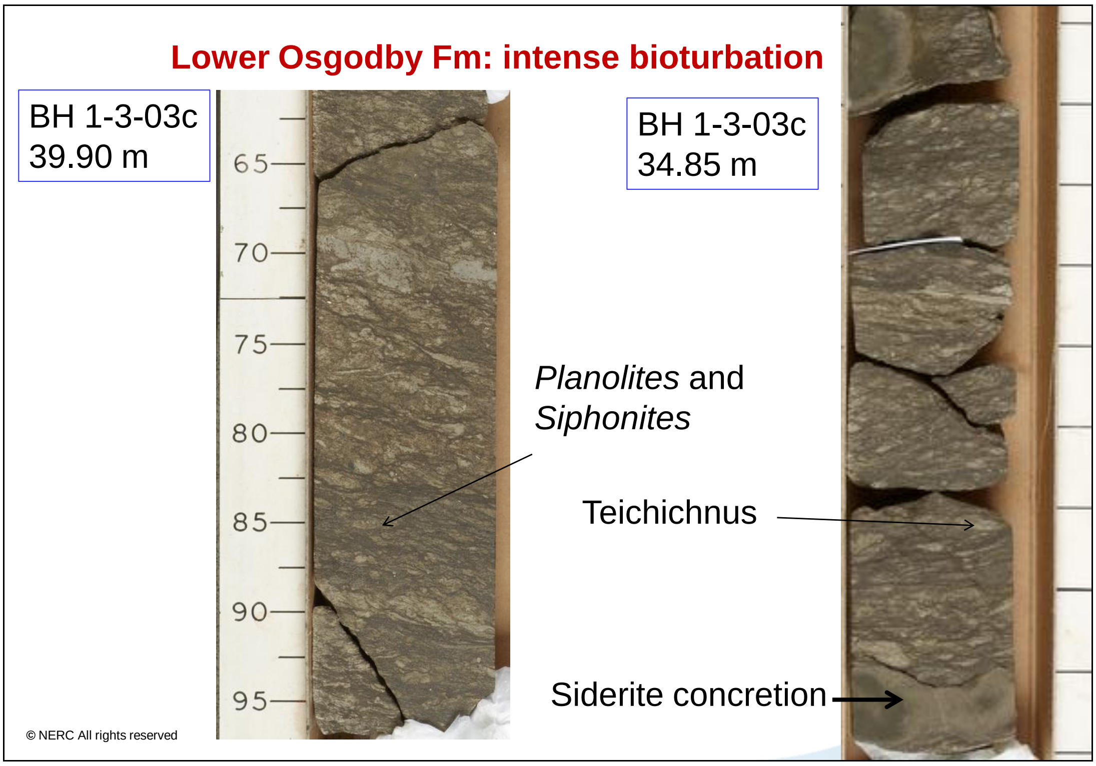


Figure 12. Examples high bioturbation index in the lower Osgodby Formation (Red Cliff Rock Member); BH 1-3-03C.

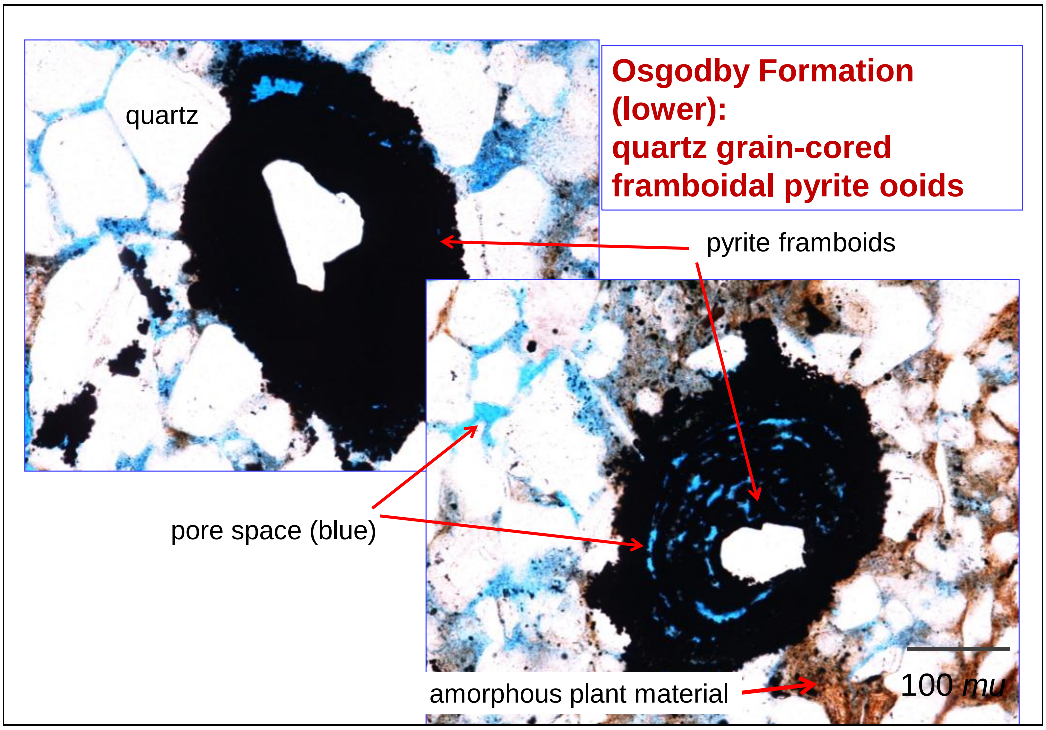


Figure 13. Examples of pyrite ooids in the lower Osgodby Formation (Red Cliff Rock Member); BH1-3-03C @ 39.95 m. Pale blue is artificially impregnated pore space; note the low proportion of amorphous plant material in the burrow-fill (clean sand) compared to surrounding sand.

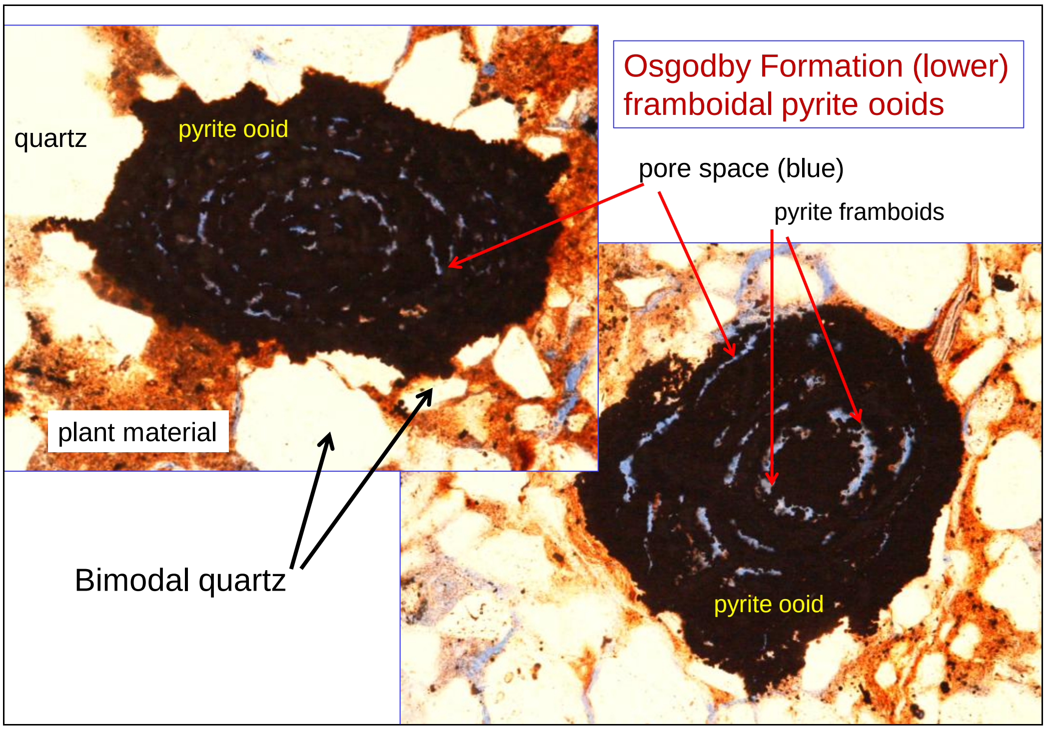


Figure 14. Examples of pyrite ooids composed of small pyrite framboids in the lower Osgodby Formation (Red Cliff Rock Member); BH1-3-03C @ 34.48 m. Pale blue is artificially impregnated pore space; note the high proportion of amorphous plant material (brown).

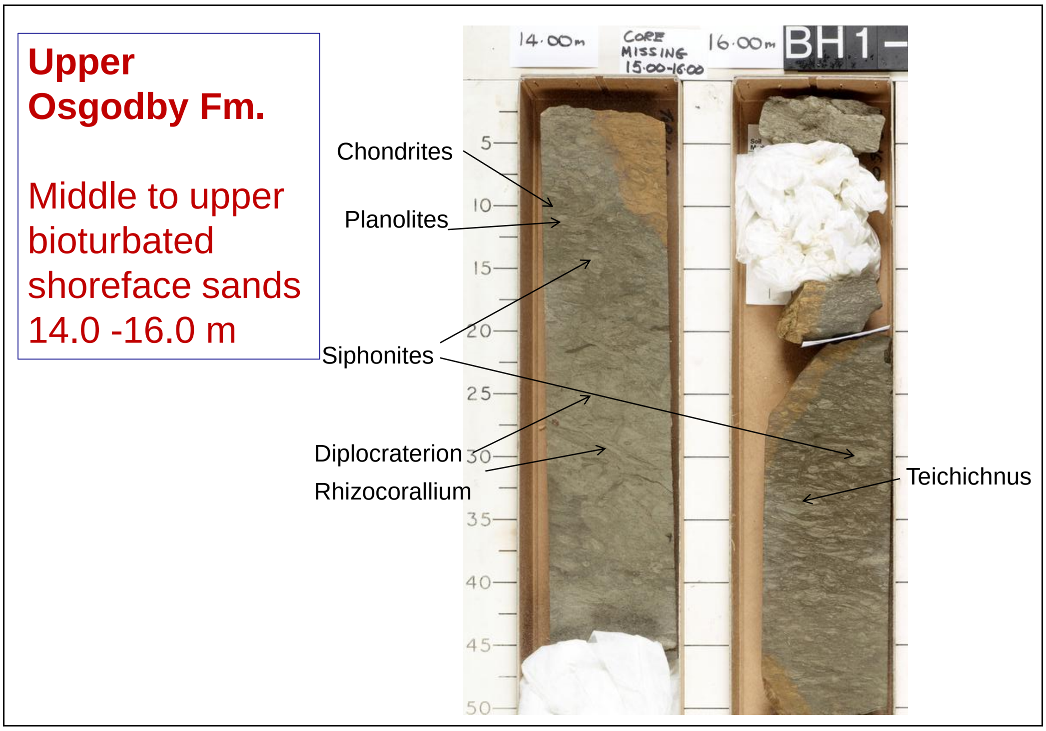


Figure 15. Examples high bioturbation index in the upper lower Osgodby Formation (Langdale Member); BH 1-3-03C; note the high proportion of 'vertical' burrows.

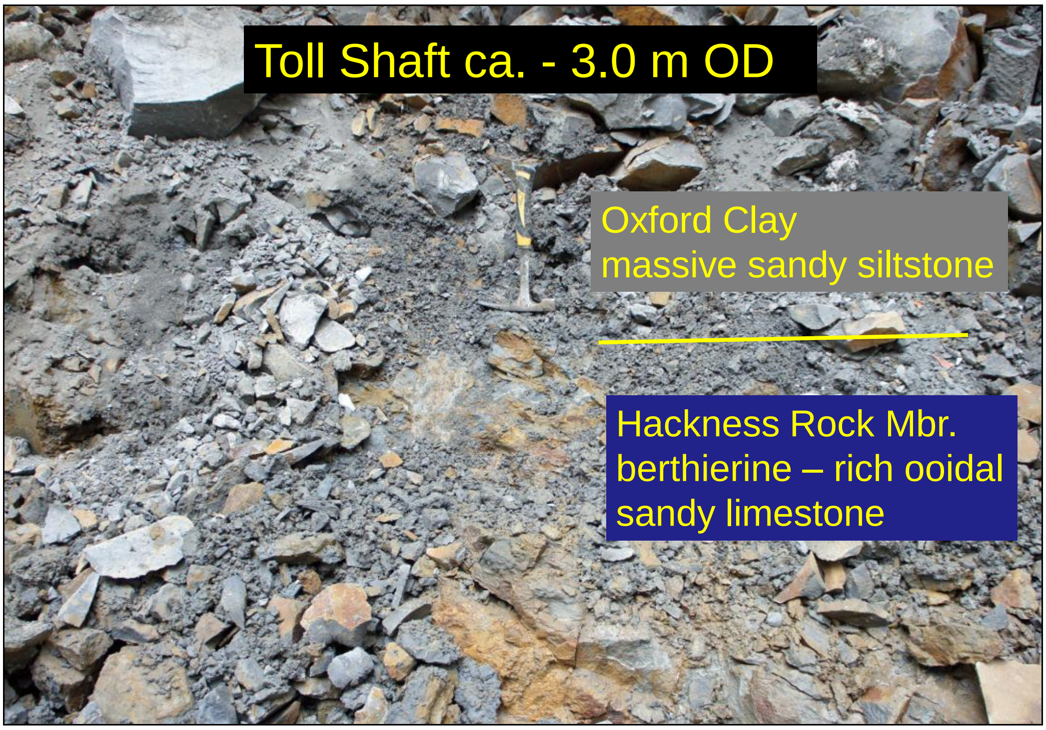


Figure 16. Boundary between the Hackness Rock Member and Oxford Clay Formation (at hammer head) in the Toll House shaft at -3.0 m OD. Hammer length 0.25 m. Upthrow side of Toll House Fault.

Figure 17. Osgodby Formation exposed at South Toll House Cliff, with intensive bioturbation in the upper part of the Langdale Member and shell bed at the base of the Hackness Rock Member (inset, left) . See also Figure 2 for orientation. Photographs: J H Powell.

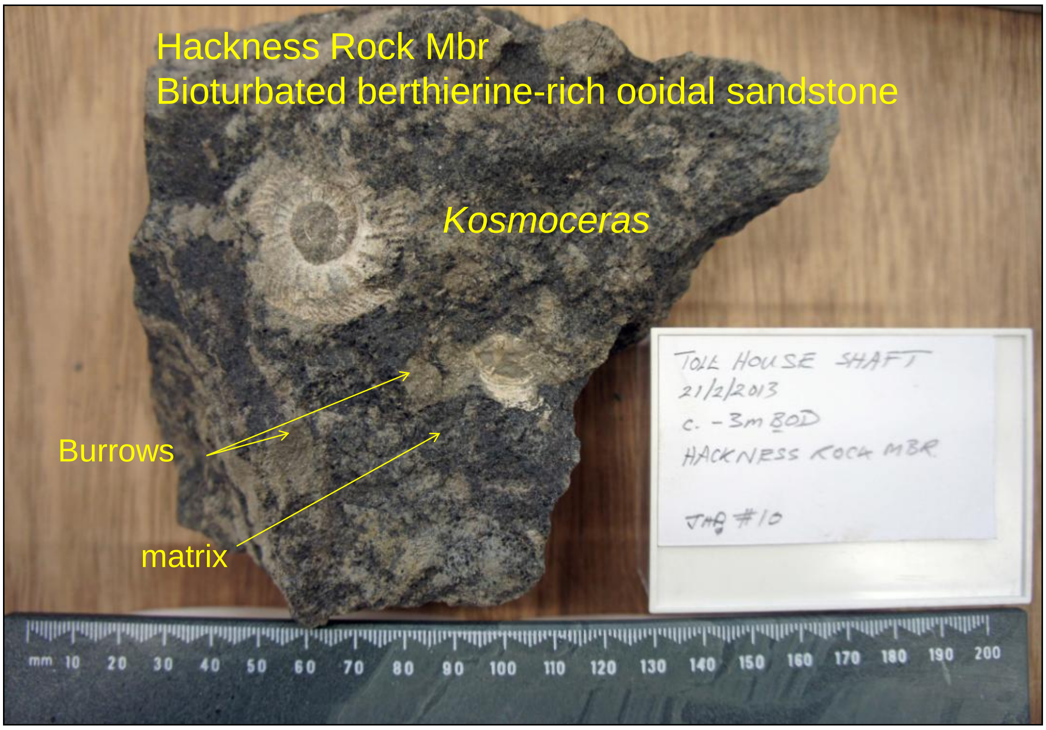


Figure 18. Highly bioturbated Hackness Rock Member with *Kosmoceras* ammonite. Toll House shaft @ ca. -3.0 m depth. Upthrow side of Toll House Fault.

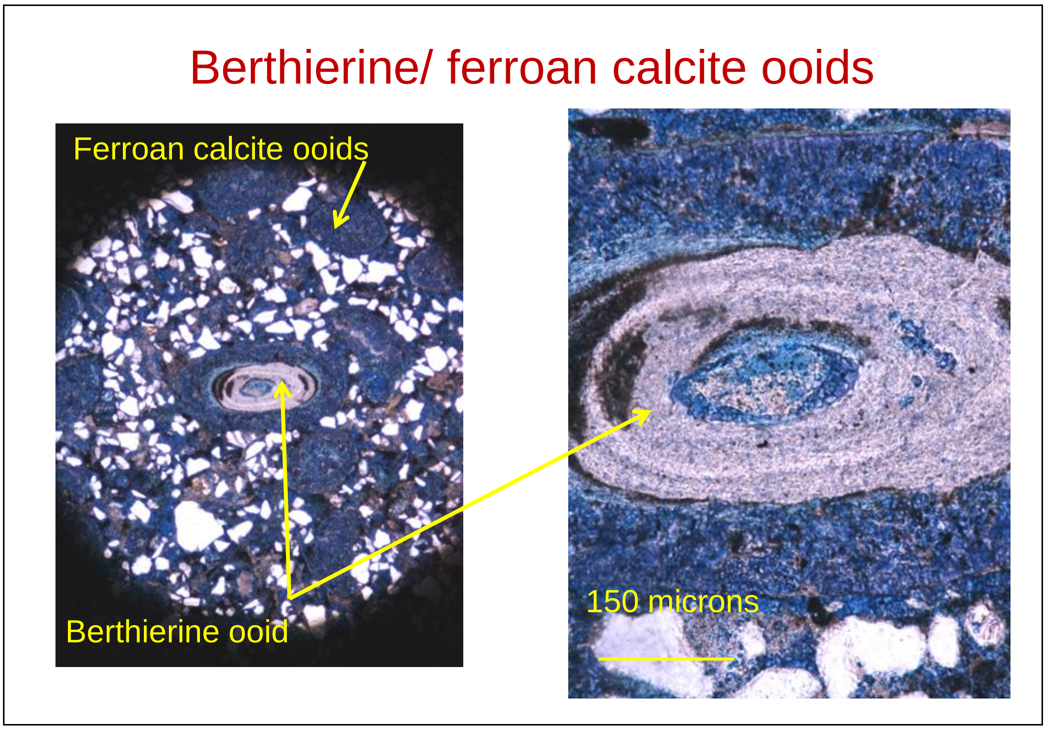


Figure 19. Stained photomicrograph of the Hackness Rock Member, showing quartz sand (white) and oblate berthierine ooids, mostly altered to calcite (blue = ferroan calcite). BH1-3-03C @12.15 m.

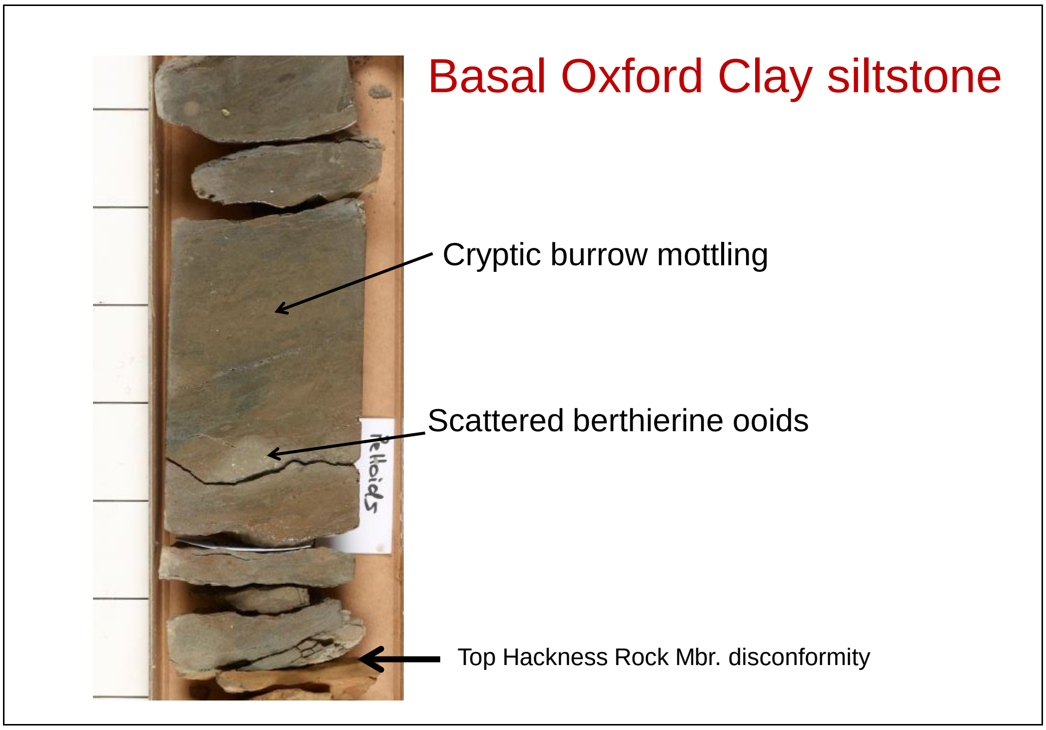


Figure 20. Boundary @11.70 m between the Hackness Rock Member and the lower Oxford Clay in BH 1-3-03C. Note the scattered berthierine ooids (white spots) and the general cryptic burrow mottling.

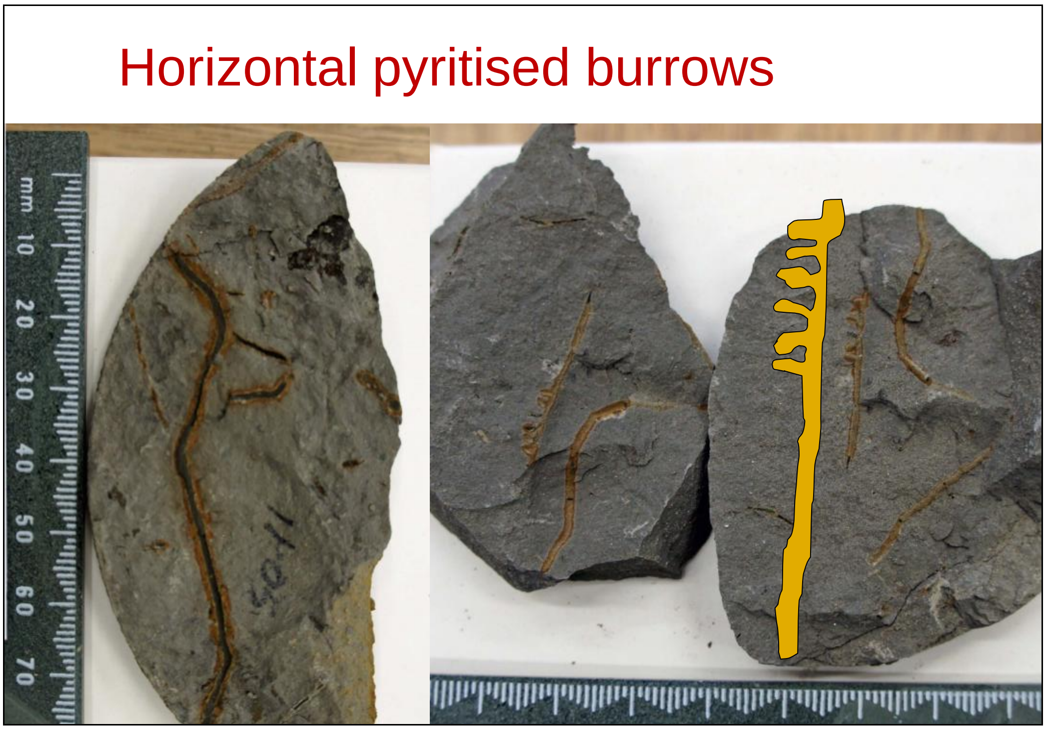


Figure 21. Pyritised burrows parallel to bedding in the lower Oxford Clay Formation, showing limonitic (pale brown halo) at 11.05 m in BH1-3-03C. Single sided protuberances are illustrated in the enlarged line drawing.

Figure 22. Excavations in the shaft at -1.5 m depth, within the lower Oxford Clay. Photographs: J H Powell

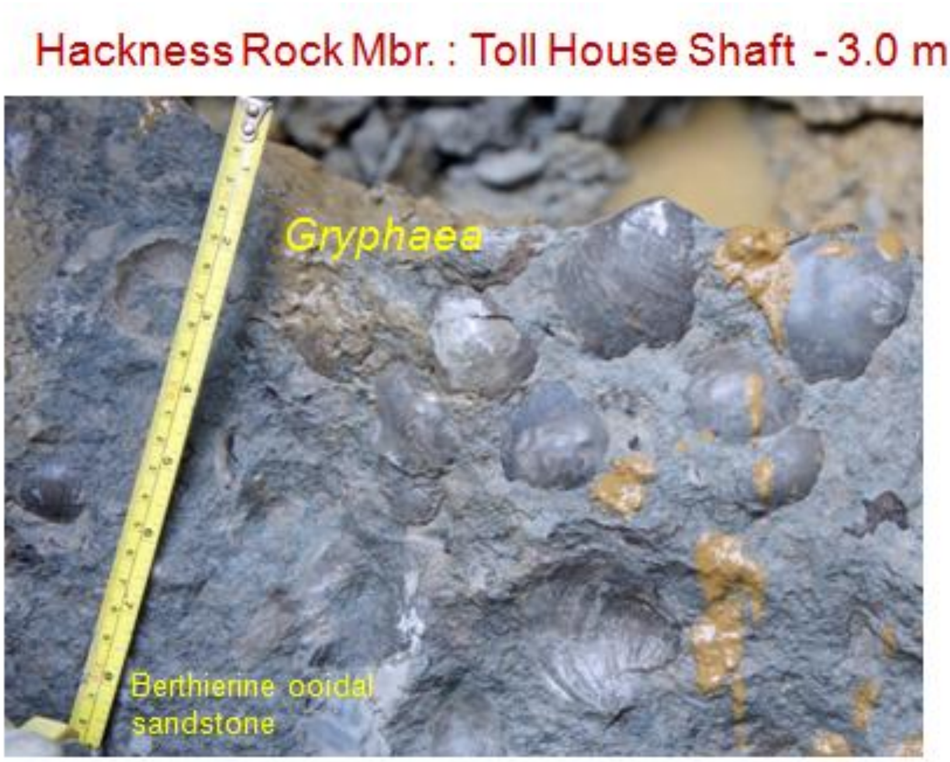


Figure 23. Cluster of *Gryphaea* bivalves (oyster) in blue-grey (unweathered) berthierine ooidal sandy limestone (Hackness Rock Member) at -3.0 m on the upthrow side of the fault in the shaft. Photograph: J H Powell.

Figure 24. Trace of the Toll House Fault in the shaft at -14 m OD showing Oxford Clay Formation (downthrow) against Osgodby Formation (Langdale Member); north arrow is approximate Photograph: J H Powell

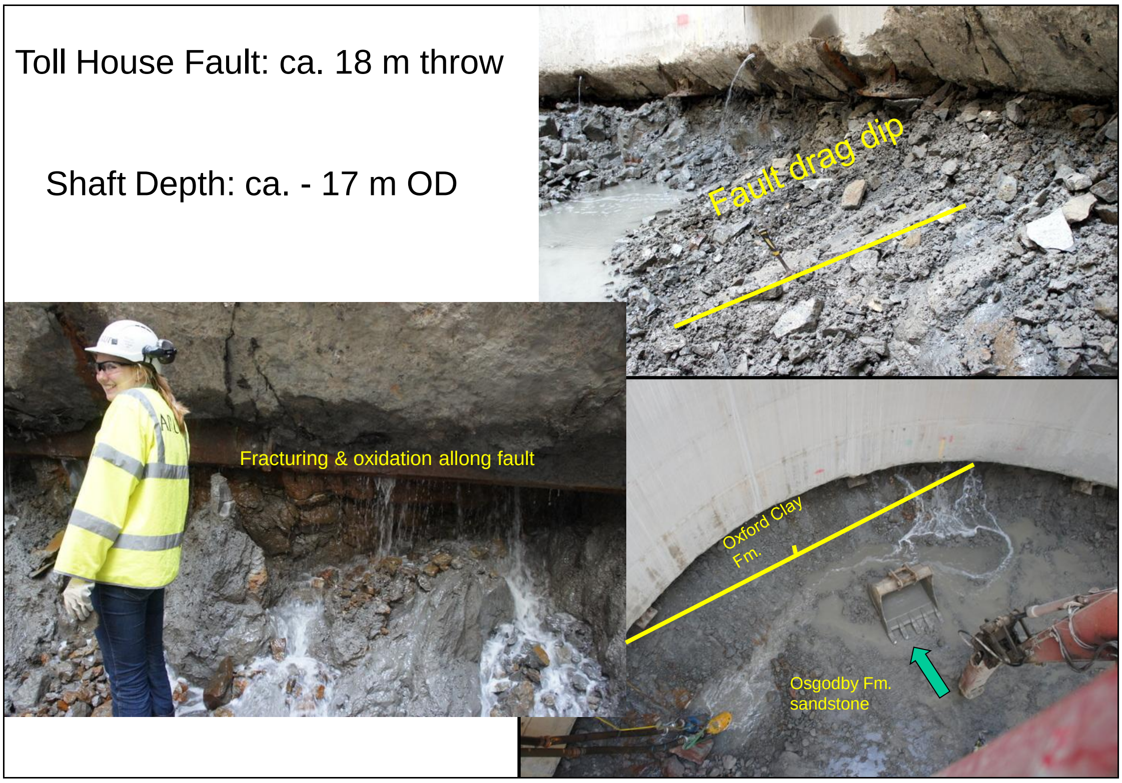


Figure 25. Trace of the Toll House Fault in the shaft at -17 m OD showing Oxford Clay Formation and underlying Hackness Rock Member (downthrow NNE) against Osgodby Formation sandstone (possibly Red Cliff Rock Member). Inset, left, shows yellow brown oxidative weathering, calcite and pyrite along fault fractures in the Hackness Rock, and high flow of saline groundwater. Inset, top right shows ca. 20 ° dip to 110 ° N (fault drag) in the Oxford Clay (upthrow). Photographs: J H Powell.

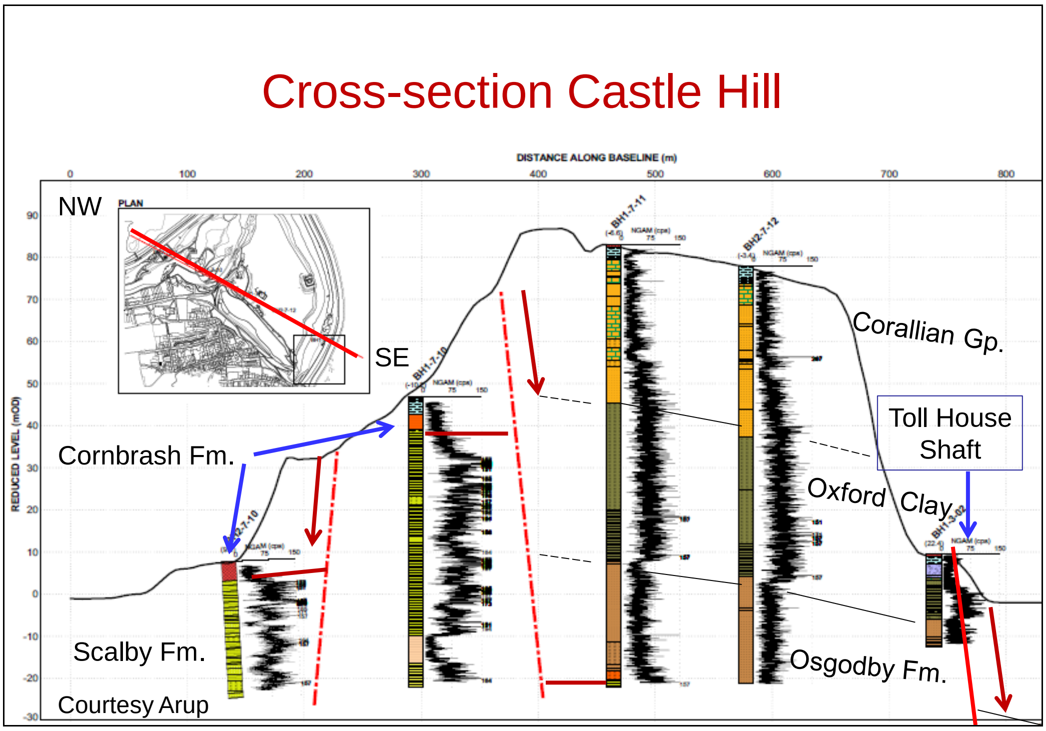


Figure 26. Cross-section NW-SE across Castle Hill showing additional boreholes with gamma-ray logs drilled for the tunnel option, showing the throw on the major Castle Hill faults and the new Toll House Fault (right).. Inset map shows orientation of section. Original Figure courtesy of Arup

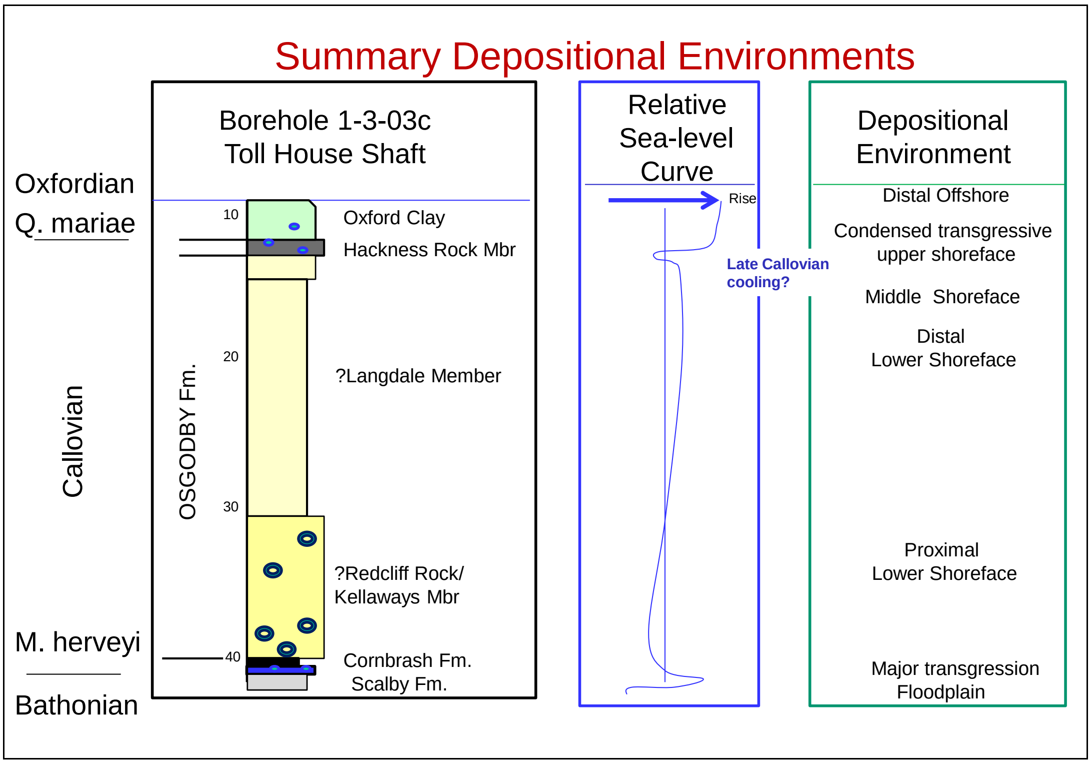


Figure 27 Summary geological section, sea-level curve and depositional environments for the Bathonian to Lower Oxfordian succession at Toll Hose based on BH 1-3-03C.

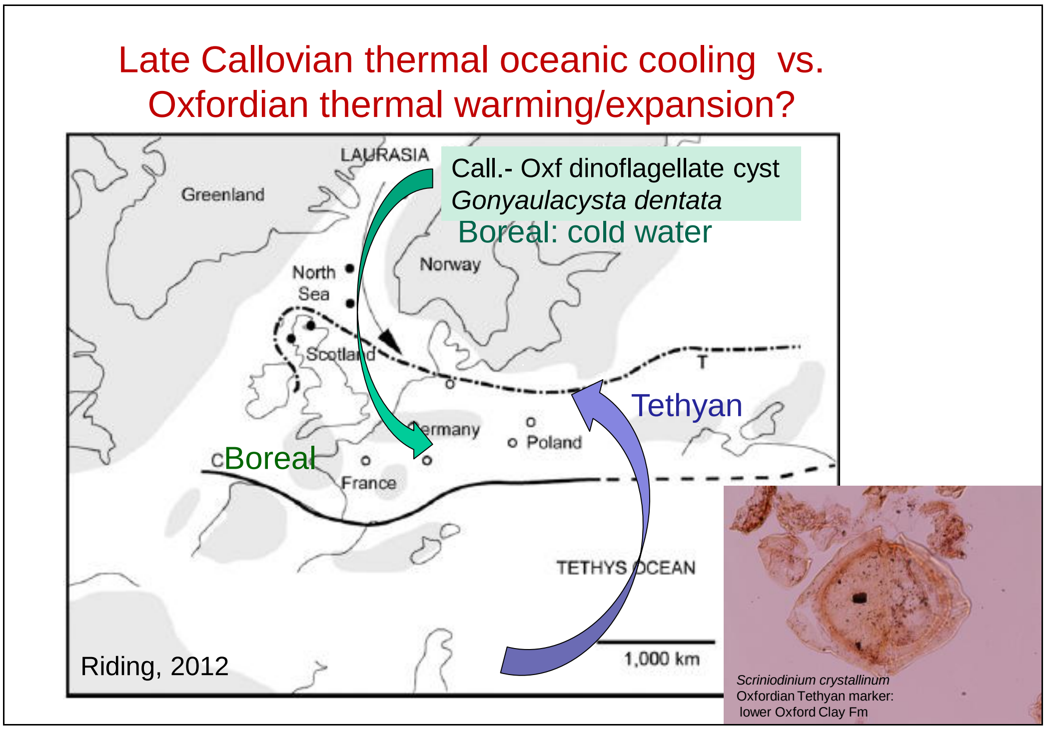


Figure 28. Palaeoceanography during the Late Callovian to Early Oxfordian times and the distribution of the cold water (boreal) dinoflagellate cyst *Gonyaulacysta dentata* and the warm water Tethyan species *Scriniodinium crystallinum* (inset; lower Oxford Clay Formation; BH1 3-03C) possibly indicating oceanic thermal expansion during the Early Oxfordian (after Riding, 2012).

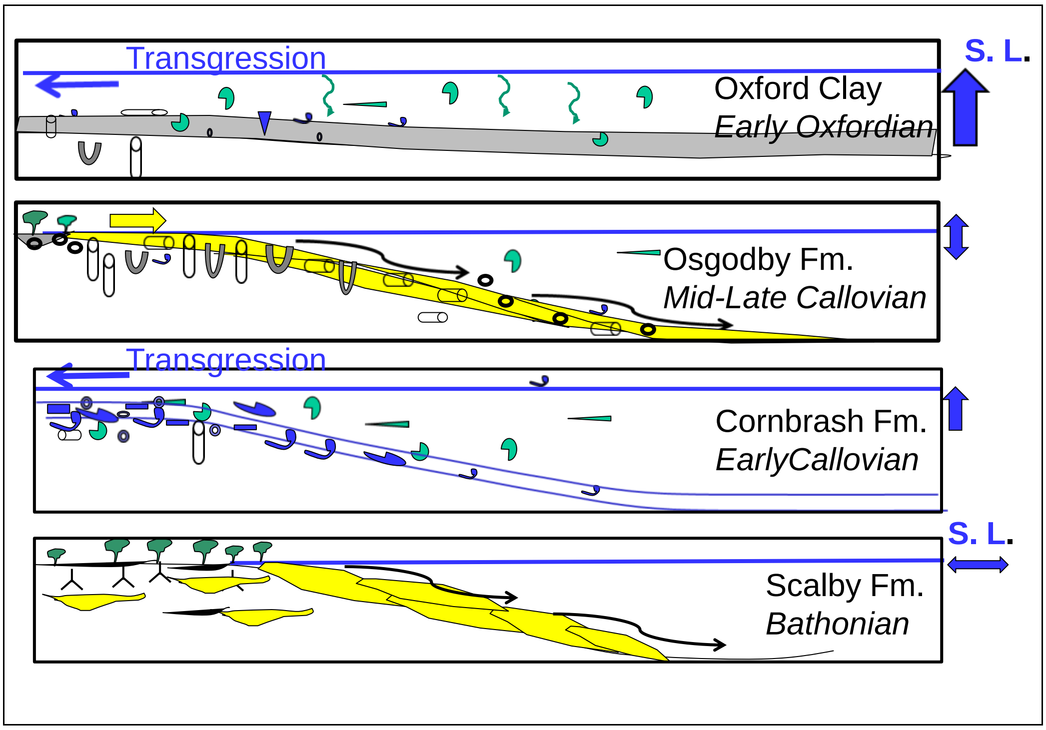


Figure 29. Evolution of depositional environments during Bathonian to Early Oxfordian time in response to sea-level fluctuations. Scalby Formation: alluvial plain with thin coals and plants (onshore) and delta sands (offshore); Cornbrash Formation: rising sea-level, marine transgression and condensed, sandy shelly ooidal carbonates; Osgodby Formation: pyrite ooids developed in lagoons and swept offshore with quartz sand during storm events; Oxford Clay Formation: widespread transgression and rising sea-level, silts and clays. See also Figure 25.

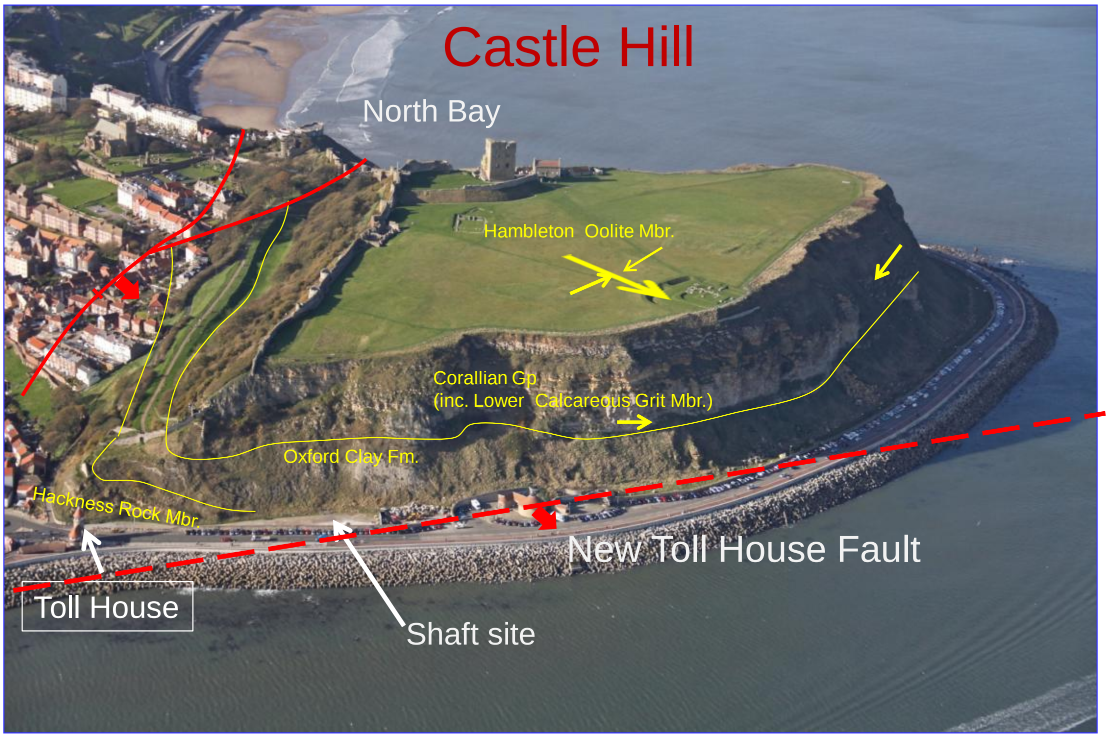


Figure 30. Castle Hill showing the approximate trace of the new Toll House Fault; red ticks show downthrow side of faults. Original photograph courtesy of Peter Smith.