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A palynological investigation of the Upper Pliensbachian and Lower Toarcian strata at Brown's Hill Quarry, Holwell, Leicestershire

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A palynological investigation of the Upper Pliensbachian and Lower Toarcian strata at Brown's Hill Quarry, Holwell, Leicestershire

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Foreword

This report presents the results of a palynological study of the Upper Pliensbachian and Lower Toarcian strata of Brown's Hill Quarry, Holwell, Leicestershire as part of the East Midlands Project.

Contents

Summary

The fourteen samples from Brown's Hill Quarry produced palynofloras of variable productivity. The lowermost sample from the uppermost Dyrham Formation produced an extremely sparse palynoflora, which is consistent with a late Pliensbachian age but is unable to refine this assessment. This sandstone unit appears to be primarily organic-lean and/or deeply weathered. Five samples from the overlying Marlstone Rock Formation also yielded sparse palynofloras of low diversity. These are dominated by pollen and spores, but also include some marine microplankton and forms such as *Halosphaeropsis liassica* are consistent with the late Pliensbachian-early Toarcian interval. The range bases of the dinoflagellate cysts ?*Luehndea spinosa,* ?*Mancodinium semitabulatum, Nannoceratopsis deflandrei* and *Scriniocassis weberi* are also consistent with the Pliensbachian-Toarcian transition. The occurrence of ?*Luehndea*

spinosa in sample 4 indicates that it is probably no younger than the *Dactylioceras tenuicostatum* standard (ammonite) zone. The palynomorphs from the Marlstone Rock Formation at this locality are less abundant than those from coeval strata at Tilton Railway Cutting. It is possible that the organic material at Holwell was winnowed away in a high-energy depositional setting. The eight samples from the Whitby Mudstone Formation all produced abundant palynofloras of moderate diversity; amorphous organic material is also present in relatively high proportions. The palynofloras are all dominated by *Halosphaeropsis liassica* and other miscellaneous microplankton and dinoflagellate cysts are more diverse and prominent. These floras are entirely consistent with the early Toarcian. High levels of *Halosphaeropsis liassica*, other prasinophytes, rare dinoflagellate cysts and abundant amorphous organic material is indicative of the most intense part of the early Toarcian anoxic event, in the *Harpoceras falciferum* standard (ammonite) zone. Also, the co-occurrences of the dinoflagellate cysts *Mancodinium semitabulatum*, *Nannoceratopsis deflandrei* subsp. *deflandrei*, *Nannoceratopsis deflandrei* subsp. *senex* and *Nannoceratopsis gracilis* are characteristic of the earliest Toarcian. For example, the range bases of the dinoflagellate cyst *Nannoceratopsis gracilis* and the pteridophytic spore *Ischyosporites variegatus* are interpreted to be early Toarcian markers.

The foraminifera and ostracods from this succession include several key late Pliensbachian and early Toarcian marker forms.

1 Introduction

A suite of fourteen samples from the Dyrham, Marlstone Rock and Whitby Mudstone formations of Brown's Hill Quarry, Holwell, Leicestershire were examined for palynomorphs in order to attempt a biostratigraphical breakdown of this important Upper Pliensbachian and Lower Toarcian section. The succession is located at NGR SK 742 235 (Clements, 1989) and comprises the *Pleuroceras spinatum, Dactylioceras tenuicostatum* and *Harpoceras falciferum* standard (ammonite) zones. A similar succession from Tilton Railway cutting, Leicestershire was recently investigated (Riding, 2001). This report and the present study are part of a review of the stratigraphy of the late Pliensbachian and early Toarcian of Leicestershire.

2 Sample Details

Sample details are given below as two lists. In the first list, the columns represent the (informal) sample number, the BGS micropalaeontological/palynological registration number (prefixed MPA), the lithostratigraphical unit, the standard (ammonite) zone, the bed number of Hallam (1968), the lithology and relative depth details respectively. The samples were collected by the author on the 12th December 2001. MRF = Marlstone Rock Formation. The second list gives more detailed lithological descriptions.

14	MPA 50791	Whitby Mudstone Fm.	*H. falciferum*	9	shale	316 cm from top MRF
13	MPA 50792	Whitby Mudstone Fm.	*H. falciferum*	9	shale	216 cm from top MRF
12	MPA 50793	Whitby Mudstone Fm.	*H. falciferum*	9	shale	136 cm from top MRF
11	MPA 50794	Whitby Mudstone Fm.	*H. falciferum*	9	clay	95 cm from top MRF
10	MPA 50795	Whitby Mudstone Fm.	*H. falciferum*	9	limestone	95 cm from top MRF

9	MPA 50796	Whitby Mudstone Fm.	*H. falciferum*	9	mudstone	70 cm from top MRF
8	MPA 50797	Whitby Mudstone Fm.	*H. falciferum*	9	mudstone	40 cm from top MRF
7	MPA 50798	Whitby Mudstone Fm.	*H. falciferum*	9	mudstone	20 cm from top MRF
6	MPA 50799	Marlstone Rock Fm.	*D. tenuiserratum*	7	limestone	Uppermost part of MRF
5	MPA 50800	Marlstone Rock Fm.	*D. tenuiserratum*	7	limestone	116cm below top MRF
4	MPA 50801	Marlstone Rock Fm.	*D. tenuiserratum*	7	limestone	230 cm below top MRF
3	MPA 50802	Marlstone Rock Fm.	*?D. tenuiserratum*	7	limestone	90 cm above base MRF
2	MPA 50803	Marlstone Rock Fm.	*P. spinatum*	7	limestone	L./most ¾ cm MRF
1	MPA 50804	Dyrham Formation	*P. spinatum*	5	sandstone	20 cm below base MRF

14	Dark grey/black, blocky, unweathered 'paper shale' - top of the 'paper shales'.
13	Grey, highly-laminated, fissile ('paper') shale - middle of the 'paper shales'.
12	Grey, highly-laminated, fissile ('paper') shale - base of the 'paper shales'.
11	Matrix - dark brown,ochreous-stained clay.
10	Brown calcareous concretions.
9	Massive, grey/mottled/ochreous blocky mudstone with scattered bivalves.
8	Massive, light grey/brown, blocky, micaceous mudstone.
7	Blocky, mid grey/brown, shelly, silty mudstone.
6	Brown/red, belemnite-bearing limestone.
5	Cross-bedded, highly crinioidal limestone.
4	Massive, dark brown, shelly, limestone.
3	Massive, dark brown, limestone.
2	Dark brown, shelly limestone.
1	Brown sandstone.

3 Lithostratigraphy and macrofaunal biostratigraphy

Brown’s Hill Quarry is part of a larger complex of disused ironstone workings east of the hamlet of Holwell, Leicestershire (Clements, 1989). The quarry used to work the Marlstone Rock Formation initially for building stone, then subsequently for iron ore. This locality is located on 1” sheet 142 and is now a geological SSSI; it represents an excellent exposure of the Middle and Upper Lias. The basal strata exposed represent the uppermost Dyrham Formation, which comprises brown, ferruginous sandstones with abundant bivalves. The lower mudstone facies of the Dyrham Formation are not exposed. This unit was previously termed the Sandrock and was previously included in the Marlstone Rock Formation. The Marlstone Rock Formation of current usage (i.e. the Ironstone) overlies the Dyrham Formation. This unit at Holwell is *c*. 4.3 m of a hard, cross-bedded, fossiliferous, chamosite oolite. Calcite and siderite are also present and the Marlstone Rock Formation is extremely fossiliferous. Brachiopods, often concentrated in ‘nests’, bivalves and belemnites are common throughout. At the top of the formation there is a concentration (‘pavement’) of belemnites, which may be a remanié deposit which represents a hiatus. In an unpublished log, K. Ambrose recognised three distinct beds. The uppermost strata at Brown's Hill Quarry are the grey shales with abundant macrofaunas and occasional concretions of the Whitby Mudstone Formation. Clements (1989, fig. 3) illustrated a simplified graphic log of the section. K. Ambrose logged 2.8 m of the Whitby Mudstone Formation at Holwell and recognised four beds. The lowermost part of the succession comprises grey-brown mudstone underlain and overlain by harder, more calcareous mudstones. These beds have yielded ammonites, bivalves, echinoids and fish remains. The youngest strata exposed are *c*. 1.9 m of dark grey, finely laminated and fissile ('paper') shales. These paper shales represent part of the maximum extent of the widespread early Toarcian anoxic event (Bucefalo Palliani *et al*., 2002). The anoxic marine conditions were not conducive to benthic biotas and also affected planktonic organisms. Consequently the macrofauna is sparse, however occasional ammonites (harpoceratids and dactylioceratids) and bivalves are present. The 'Oolite Member' of Clements (1989) was not exposed at the time of sampling. This locality was also mentioned by Lamplugh *et al*. (1909), Kent (1937), Hallam (1955) and Swift and Reddish (2002).

The Sandrock and the Marlstone Rock Formation were originally correlated to the *Pleuroceras spinatum* standard (ammonite) zone. However, Hallam (1955) reported Lower Toarcian ammonites in the Ironstone facies. Howarth (1958) subsequently reported *Pleuroceras spinatum* from the Sandrock of central England and, on this basis, both the Sandrock and the Marlstone Rock Formation were placed into the *Pleuroceras spinatum* standard (ammonite) zone. This author assigned the Sandrock to the *Pleuroceras apyrenum* standard (ammonite) subzone and the Ironstone to the *Pleuroceras hawskerense* standard (ammonite) subzone (see Howarth, 1980a). Clements (1989) stated that ammonites are absent in the Dyrham and Marlstone Rock formations at Brown's Hill Quarry. However, a specimen of *Pleuroceras* sp. has been found in a loose block of the Marlstone Rock Formation at the quarry. Ammonites characteristic of the *Dactylioceras tenuicostatum* standard (ammonite) zone have not been recorded at Holwell. This is consistent with the lowermost part of the formation being assigned to the *Pleuroceras spinatum* standard (ammonite) zone (Howarth, 1980a, fig. 8A; Sumbler and Ivimey-Cook, 1996). However, due to regional evidence (Hallam, 1955; Howarth, 1980a,b), the majority of the Marlstone Rock Formation is deemed to be within the *Dactylioceras tenuicostatum* standard (ammonite) zone. A comprehensive account of the microfaunas from this locality has been given by Wilkinson (in preparation).

4 Palynofloras from the Brown's Hill Quarry succession

The distribution of all palynomorphs from the Brown's Hill Quarry samples are illustrated in Table 1. The samples were prepared in two ways. One subset was prepared using the traditional mineral acid digestion technique. Another set was prepared using sodium hexametaphosphate, a technique developed recently in the BGS palynology laboratory. This chemical disaggregates sedimentary rocks, thereby allowing palynomorphs to be isolated. The set prepared using sodium hexametaphosphate proved to be the most productive and therefore these data are described herein.

This new preparation technique appears to give extremely similar results to those derived by the traditional method. The majority of the data in Table 1 are derived from the slides prepared using sodium hexametaphosphate. However, where the acid method slides gave palynomorph occurrences which were not observed in the sodium hexametaphosphate slides, these are included in Table 1 in square brackets. The relative sparsity of these occurrences is a testament to the utility of this new preparation method. Samples 3, 4 and 14 do not have any palynomorph occurrences which were recorded only in the acid-method slides. There may, however, be certain palynomorph groups best suited to individual methods. For example, four out of the five samples which yielded foraminiferal test linings were those prepared using acid maceration. (Table 1). The pollen grain *Perinopollenites elatoides* and the spores *Contignisporites* spp. and *Todisporites minor* are present more often in samples prepared using mineral acids (Table 1).

Furthermore, dinoflagellate cysts are more diverse in samples 5 and 11 which were prepared using acid, as compared to these prepared using sodium hexametaphosphate. These differences are relatively minor and most probably fall into the range of natural variability.

4.1 THE DYRHAM FORMATION (SAMPLE 1)

Sample 1 was taken from the uppermost part of the Dyrham Formation, which is referable to the *Pleuroceras spinatum* standard (ammonite) zone (*Pleuroceras apyrenum* standard (ammonite) subzone) according to Howarth (1980a, fig. 8A). The sample produced an extremely sparse, low diversity palynoflora which is poorly-preserved (Table 1). These are accompanied by moderate levels of wood fragments and plant tissue. Palynomorph taxa identified include *Halosphaeropsis liassica* and *Tasmanites* spp. (indigenous marine) and *Cerebropollenites macroverrucosus* and *Classopollis classoides* (terrestrially-derived). This association confirms the marine depositional setting and is consistent with a late Pliensbachian age, but cannot refine it. *Halosphaeropsis liassica* is highly characteristic of the late Pliensbachian-early Toarcian interval (Bucefalo Palliani and Riding, 2000). This sandstone unit appears to be primarily organic-lean. The common modern fungal debris and frequent modern plant tissues and spore/pollen contaminants are also indicative of deep weathering. The Dyrham Formation of Tilton Railway Cutting, by contrast, is extremely palynologically productive (Riding, 2001).

4.2 THE MARLSTONE ROCK FORMATION (SAMPLES 2 TO 6)

The lowermost Marlstone Rock Formation is correlated with the *Pleuroceras spinatum* standard (ammonite) zone. This is consistent with the specimen of *Pleuroceras* sp., which was found in a loose block of the Marlstone Rock Formation at this locality. The remaining four samples are all assigned to the *Dactylioceras tenuicostatum* standard (ammonite) zone based on regional evidence. These five samples from the Marlstone Rock Formation all yielded relatively sparse palynofloras of low diversity (Table 1). The preservation of palynomorphs throughout is poor. The kerogen associations are also sparse with common woody tissue, other plant tissues and mineral grains. The palynofloras are dominated by pollen and spores comprising bisaccate pollen, *Cerebropollenites macroverrucosus, Chasmatosporites* spp., *Classopollis classoides, Cyathidites* spp., *Dictyophyllidites* spp., *Osmundacidites wellmanii* and *Perinopollenites elatoides.* A single, questionable specimen of *Callialasporites microvelatus* was noted in sample 4. Reworked Carboniferous spores, *Cingulizonates/Densosporites* and *Lycospora pusilla*, were recovered from samples 3, 4 and 6. The miscellaneous marine microplankton associations are similar in composition to that from the Dyrham Formation, although these forms are more common (Table 1). In addition to *Halosphaeropsis liassica* and *Tasmanites* spp., small numbers of foraminiferal test linings and *Micrhystridium* were observed. *Halosphaeropsis liassica* is present as clumps of individuals. In large proportions and associated with abundant amorphous organic material, these characterise the early Toarcian anoxic facies (Woollam and Riding, 1983; Bucefalo Palliani and Riding, 2000). Additionally, minor proportions of poorly preserved dinoflagellate cysts are present. Sample 3 produced questionable single specimens of *Luehndea spinosa* and *Mancodinium semitabulatum*. Sample 5 proved the most productive with *Nannoceratopsis deflandrei* subsp. *deflandrei*, *Nannoceratopsis deflandrei* subsp*. senex* and *Scriniocassis weberi* present in the subsample prepared using mineral acids (Table 1). The uppermost sample, number 6, yielded ?*Nannoceratopsis deflandrei* subsp*. senex* and possible indeterminate forms.

The spore-pollen and miscellaneous microplankton associations are consistent with the late Pliensbachian-early Toarcian interval. The specimen of ?*Callialasporites microvelatus* is interesting; this genus is not normally present in strata younger than late Toarcian (Riding *et al*., 1991). The algal form *Halosphaeropsis liassica* is characteristic of the late Pliensbachian-early Toarcian (Bucefalo Palliani and Riding, 2000). The inceptions of the dinoflagellate cysts ?*Luehndea spinosa,* ?*Mancodinium semitabulatum, Nannoceratopsis deflandrei* and

Scriniocassis weberi in this unit are consistent with the Pliensbachian-Toarcian boundary. All these species have range bases in the late Pliensbachian (Morgenroth, 1970; Riding and Thomas, 1992). The absence of dinoflagellate cysts in samples 1 to 3 at this locality is attributed to facies control. *Luehndea spinosa* has the shortest stratigraphical range, from the late Pliensbachian to the earliest Toarcian (Riding, 1987). The occurrence of ?*Luehndea spinosa* in sample 4 means that this horizon is probably no younger than the *Dactylioceras tenuicostatum* standard (ammonite) zone. The palynofloras recovered from the Marlstone Rock Formation at Holwell are significantly less abundant than those from this unit at Tilton Railway Cutting, Leicestershire (Riding, 2001). To explain this disparity, it is possible that the Marlstone Rock Formation section at Holwell is highly and deeply weathered. However, it seems more likely that the organic elements in this unit at Holwell have been winnowed in a high energy regime evidenced by the cross bedding. At Tilton Railway Cutting, the inception of the Toarcian anoxic event was observed in the uppermost Marlstone Rock Formation (Riding, 2001). This major event is manifested palynologically by abundant *Halosphaeropsis liassica* and common/abundant amorphous organic material. This was not present at Holwell and is further evidence of a hiatus between the Marlstone Rock and Whitby Mudstone formations at this locality (see section 3).

4.3 THE WHITBY MUDSTONE FORMATION (SAMPLES 7 TO 14)

The uppermost eight samples are all from the Whitby Mudstone Formation and are assigned to the *Harpoceras falciferum* standard (ammonite) zone, based both on regional and local evidence. Note that samples 10 and 11 are nodular limestone and clay matrix respectively from the same horizon. The eight Whitby Mudstone Formation samples produced abundant palynofloras of moderate diversity (Table 1); the preservation throughout is good. The kerogen assemblages are similarly abundant, with common amorphous organic material, wood fragments and other plant tissues. Amorphous organic material is especially abundant in samples 12 to 14 which represent the 'paper shale' facies. The palynofloras are dominated by the algal palynomorph *Halosphaeropsis liassica* and gymnospermous pollen; other microplankton and pteridophyte spores are subordinate (Table 1). The gymnospermous pollen largely comprises undifferentiated bisaccate pollen, *Cerebropollenites macroverrucosus, Chasmatosporites* spp., *Classopollis classoides, Classopollis meyeriana* and *Perinopollenites elatiodes.* The spore floras include significant levels of *Contignisporites* spp., *Cyathidites* spp., *Dictyophyllidites* spp. and *Ischyosporites variegatus*. Lesser numbers of *Cibotiumspora juriensis*, *Concavissimisporites verrucosus, Coronatispora valdensis,* indeterminate forms, *Osmundacidites wellmanii, Retitriletes austroclavatidites* and *Todisporites* spp were also observed. The reworked Carboniferous spores, *Cingulizonates/Densosporites* and *Lycospora pusilla*, were also recorded from samples 8 to 12. The overall marine microplankton floras from the Whitby Mudstone Formation are similar to those from the underlying Dyrham and Marlstone Rock formations, although dinoflagellate cysts and miscellaneous microplankton are more diverse, and far more common (Table 1). Prasinophytes overwhelmingly dominate the marine component and these comprise *Cymatiosphaera* spp., *Halosphaeropsis liassica* and *Tasmanites* spp. *Halosphaeropsis liassica* is consistently the most abundant palynomorph form (Table 1). Other miscellaneous microplankton comprise *Botryococcus*, foraminiferal test linings, *Micrhystridium* spp. and scolecodonts. In comparison, relatively minor levels of dinoflagellate cysts were recorded. These are indeterminate forms, *Mancodinium semitabulatum*, *Nannoceratopsis deflandrei* subsp. *deflandrei*, *Nannoceratopsis deflandrei* subsp. *senex, Nannoceratopsis gracilis* and *Pareodinia* sp. *Nannoceratopsis deflandrei* subsp. *senex* is the most consistently recorded taxon and sample 11 produced the highest numbers and diversity (Table 1).

The Whitby Mudstone Formation palynofloras are entirely consistent with the early Toarcian. The algal form *Halosphaeropsis liassica* is characteristic of the late Pliensbachian-early Toarcian (Bucefalo Palliani and Riding, 2000). The association of the dinoflagellate cysts *Mancodinium semitabulatum*, *Nannoceratopsis deflandrei* subsp. *deflandrei*, *Nannoceratopsis deflandrei* subsp. *senex* and *Nannoceratopsis gracilis* are also characteristic of the earliest Toarcian (Riding *et al*., 1999). The isolated occurrence of *Nannoceratopsis gracilis* in sample 11 is especially significant because the range base of this species occurs in the early Toarcian (Riding *et al*., 1999, fig. 11). Furthermore the association of extremely high proportions of *Halosphaeropsis liassica*, the presence of *Tasmanites*, spp., relatively rare dinoflagellate cysts and common/abundant amorphous organic material indicates the most intense part of the early Toarcian axoxic event, which is within the *Harpoceras falciferum* standard (ammonite) zone (Bucefalo Palliani and Riding, 2000; Bucefalo Palliani *et al*., 2002). The uppermost beds, the 'paper shale' facies, contain the most amorphous organic material and sample 14 yielded the most specimens of *Halosphaeropsis liassica* per microscope slide (Table 1). Samples 7 to 14 herein are comparable with samples 7 to 3 at Tilton Railway Cutting of Riding (2001). Because of the anoxia caused by marine stratification, the majority of dinoflagellates could not complete their life cycle. However, prasinophytes such as *Halosphaeropsis liassica* can complete their entire life strategy in surface waters and this is why the anoxic conditions caused prasinophytes to thrive (Bucefalo Palliani and Riding, 1999; 2000; Bucefalo Palliani *et al*., 2002). The range base of *Ischyosporites variegatus* at the base of the Whitby Mudstone Formation in sample 7 is also deemed to be of biostratigraphical significance. This inception is interpreted to be a reliable early Toarcian marker (Guy, 1971; Filatoff, 1975; Riding *et al*., 1999; Riding, 2001).

4.4 SUMMARY

The fourteen samples from Brown's Hill Quarry produced palynofloras of variable productivity. The lowermost sample from the uppermost Dyrham Formation produced an extremely sparse palynoflora, which is consistent with a late Pliensbachian age but is unable to refine this assessment. This sandstone unit appears to be primarily organic-lean and/or deeply weathered.

Five samples from the overlying Marlstone Rock Formation also yielded sparse palynofloras of low diversity. These are dominated by pollen and spores, but also include some marine microplankton and forms such as *Halosphaeropsis liassica* are consistent with the late Pliensbachian-early Toarcian interval. The range bases of the dinoflagellate cysts ?*Luehndea spinosa,* ?*Mancodinium semitabulatum, Nannoceratopsis deflandrei* and *Scriniocassis weberi* are also consistent with the Pliensbachian-Toarcian transition. The occurrence of ?*Luehndea spinosa* in sample 4 indicates that it is probably no younger than the *Dactylioceras tenuicostatum* standard (ammonite) zone. The palynomorphs from the Marlstone Rock Formation at this locality are less abundant than those from coeval strata at Tilton Railway Cutting. It is possible that the organic material at Holwell was winnowed away in a high-energy depositional setting.

The eight samples from the Whitby Mudstone Formation all produced abundant palynofloras of moderate diversity; amorphous organic material is also present in relatively high proportions. The palynofloras are all dominated by *Halosphaeropsis liassica* and other miscellaneous microplankton and dinoflagellate cysts are more diverse and prominent. These floras are entirely consistent with the early Toarcian. High levels of *Halosphaeropsis liassica*, other prasinophytes, rare dinoflagellate cysts and abundant amorphous organic material is indicative of the most intense part of the early Toarcian anoxic event, in the *Harpoceras falciferum* standard (ammonite) zone. Also, the co-occurrences of the dinoflagellate cysts *Mancodinium semitabulatum*, *Nannoceratopsis deflandrei* subsp. *deflandrei*, *Nannoceratopsis deflandrei* subsp. *senex* and *Nannoceratopsis gracilis* are characteristic of the earliest Toarcian. For example, the range bases of the dinoflagellate cyst *Nannoceratopsis gracilis* and the pteridophytic spore *Ischyosporites variegatus* are interpreted to be early Toarcian markers.

5 Integration of palynological and micropalaeontological data

The palynofloras described herein and the associated calcareous microfaunas (Wilkinson, 2002) complement each other to give a comprehensive integrated micropalaeontological breakdown for the Brown's Hill Quarry section. Together with the integrated micropalaeontological information from the similar succession at Tilton Railway Cutting (Riding, 2001; Wilkinson, 2001), a significant regional synthesis emerges. Key foraminifera from the Dyrham Formation at this locality are indicative of the *Amaltheus margaritatus* standard (ammonite) zone (Wilkinson, 2002). This represents the best micropalaeontological marker because the palynoflora proved extremely sparse in this unit (see section 4.1). Furthermore, the ostracod fauna is also not especially biostratigraphically significant. The foraminifera and ostracods from the majority of the overlying Marlstone Rock Formation are, like the palynofloras, indicative of the Pliensbachian-Toarcian transition. However, the 'belemnite pavement' at the top of this unit is no younger than the *Dactylioceras tenuicostatum* standard (ammonite) zone on foraminiferal evidence (Wilkinson, 2002). Ostracods from the base of the formation appear to be typical of the early Toarcian of Rutland according to Horton and Coleman (1977). Foraminifera and ostracods from the Whitby Mudstone Formation are indicative of the early Toarcian. Samples from 20 cm to 93 cm above the base of the formation have yielded several key regional markers (Wilkinson, 2002). The 'paper shale' facies at the top of the formation proved virtually devoid of foraminifera or ostracods. This foraminifera/ostracod 'blackout event' is entirely consistent with the presence of the most intense anoxic conditions during this widespread oceanic anoxic event (see section 4.3). Evidence from elsewhere indicates that calcareous nannofossils are similarly affected (Bucefalo Palliani *et al*., 2002). Correlation with Tilton Railway Cutting and other coeval successions means that the 'paper shale' facies is referable to the *Harpoceras falciferum* standard (ammonite) zone, which is consistent with the presence of harpoceratid ammonites in this bed at Holwell.

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Sample No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Substage	UP	UP	?LT	LT	LT	LT	LT	LT	LT	LT	LT	LT	LT	LT
Ammonite Zone	Ps	Ps	?Dt	Dt	Dt	Dt	Hf	Hf	Hf	Hf	Hf	Hf	Hf	Hf
Ammonite Subzone														
Lithostratigraphy	DF	MRF	MRF	MRF	MRF	MRF	WMF	WMF	WMF	WMF	WMF	WMF	WMF	WMF
Bed Number of Hallam (1968)	5	7	7	7	7	7	9	9	9	9	9	9	9	9
Dinoflagellate cysts														
Dinoflagellate cysts - indeterminate	…	…	…	…	…	?2	…	…	?1	…	[1]	…	…	…
Luehndea spinosa	…	…	…	?1	…	…	…	…	…	…	…	…	…	…
Mancodinium semitabulatum	…	…	…	?1	…	…	…	…	…	…	[1]	2	…	3
Nannoceratopsis deflandrei subsp. deflandrei	…	…	…	…	[2]	…	…	…	2	1	4	…	…	…
Nannoceratopsis deflandrei subsp. *senex*	…	…	…	…	[7]	[?1]	3	11	29	6	37	6	…	24
Nannoceratopsis gracilis	…	…	…	…	…	…	…	…	…	…	2	…	…	…
Pareodinia sp.	…	…	…	…	…	…	…	…	…	…	[1]	…	…	…
Scriniocassis weberi	…	…	…	…	[1]	…	…	…	…	…	…	…	…	…
Miscellaneous microplankton														
Botryococcus	…	…	…	…	…	…	…	9	…	…	[2]	…	…	4
Cymatiosphaera spp.	…	…	…	…	…	…	15	27	9	7	29	5	[4]	2
Foraminiferal test linings	…	…	…	…	[1]	…	[1]	[2]	1	…	…	[4]	…	…
Halosphaeropsis liassica	1	5	12	14	27	7	3697	2872	4716	1032	2452	4322	1728	8924
Micrhystridium spp.	…	…	…	1	…	…	…	…	2	5	17	…	…	10
Scolecodont	…	…	…	…	…	…	1	…	…	…	…	…	…	…
Tasmanites spp.	4	10	3	11	6	4	47	1021	147	42	47	39	21	141
Pollen														
Bisaccate pollen - undifferentiated	3	8	26	37	30	14	33	123	211	89	1544	147	35	309
Callialasporites microvelatus	…	…	…	?1	…	…	…	…	…	…	…	…	…	…
Cerebropollenites macroverrucosus	1	2	3	6	7	2	71	274	712	174	811	247	30	597
Chasmatosporites spp.	…	[1]	…	5	9	…	27	30	48	17	89	42	41	152
Classopollis classoides	1	3	16	45	42	21	382	2481	2163	347	970	571	297	338
Classopollis meyerniana	…	…	…	…	…	…	…	457	82	[39]	42	19	…	40
Perinopollenites elatoides	…	…	2	…	[4]	…	…	…	…	…	181	[27]	…	52
Pollen - indeterminate	…	1	4	3	…	…	…	…	…	…	3	…	…	…
Spores														
Cibotiumspora juriensis	…	…	…	…	…	…	…	…	…	1	…	…	…	…
Cingulizonates/Densosporites spp. (reworked)	…	…	…	1	…	…	…	2	…	…	1	1	…	…
Concavissimisporites verrucosus	…	…	…	…	…	…	2	…	…	…	…	1	[1]	…
Contignisporites spp.	…	…	…	…	…	…	[1]	280	[7]	…	…	[3]	…	…
Coronatispora valdensis	…	…	…	…	…	…	1	4	…	…	1	3	…	3
Cyathidites australis	[1]	1	…	1	[2]	…	10	28	58	17	10	4	[6]	27
Cyathidites minor	…	2	…	2	4	…	42	209	747	161	168	20	6	71
Dictyophyllidites spp.	…	…	…	…	…	1	7	29	39	81	76	3	2	14
Ischyosporites variegatus	…	…	…	…	…	…	27	189	27	29	30	9	4	9
Lycospora pusilla (reworked)	…	…	1	4	…	[12]	…	…	1 + ?1	1	…	…	…	…
Osmundacidites wellmanii	…	[1]	…	…	…	…	…	…	…	…	2	1	…	…
Retitriletes austroclavatidites	…	…	…	…	…	…	2	…	…	…	11	…	…	1
Spores - indeterminate	1	1	…	1	1	2	9	…	…	…	2	2	…	…
Todisporites major	…	…	…	…	…	…	…	…	…	[1]	…	…	…	…
Todisporites minor	…	…	…	…	…	…	[1]	…	1	1	…	[5]	[3]	…
Numbers of palynomorphs per 'non-acid' slide	**11**	**33**	**67**	**134**	**126**	**51**	**4376**	**8046**	**8994**	**2011**	**6529**	**5444**	**2164**	**10721**
Palynomorph diversity	**7**	**11**	**8**	**16**	**14**	**10**	**20**	**18**	**20**	**19**	**27**	**23**	**13**	**19**

Table 1. The stratigraphical distribution of palynomorphs in the fourteen samples studied. The palynomorphs are listed alphabetically within four groups. The numbers represent numbers of specimens per microscope slide. Three dots (…) indicate that the form is absent. The main body of data are those observed in subsamples prepared using sodium hexametaphosphate as a disaggregant (see section 4). However, cells with numbers in square brackets ([]) represent occurrences noted only in the samples prepared using the traditional acid preparation procedure.

Abbreviations:

UP - Upper Pliensbachian

LT - Lower Toarcian

Ps - *Pleuroceras spinatum* standard (ammonite) zone

Dt – *Dactylioceras tenuicostatum* standard (ammonite) zone

Hf - *Harpoceras falciferum* standard (ammonite) zone

DF - Dyrham Formation

MRF - Marlstone Rock Formation

WMF - Whitby Mudstone Formation