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Short communication

The lithostratigraphical context of the English Chalk Rock (Turonian)

Mark A. Woods [a,*], Andrew R. Farrant [a], Andrew J. Newell [b], Kathryn A. Lee [a]

[a] British Geological Survey, Keyworth, Nottingham, NG12 5GG, UK
[b] British Geological Survey, Maclean Building, Wallingford, OX10 8BB, UK

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A B S T R A C T

Correlations of borehole geophysical logs in the middle and upper Turonian Chalk Group are used to consider recent proposals for a revision in understanding of a unit of hardgrounds (Chalk Rock) and associated stratigraphy developed across parts of southern England. Along the northern edge of the London and Wessex basins, geophysical logs reveal a laterally continuous framework of correlatable inflection patterns in the New Pit Chalk, with the package of sediment immediately below the Chalk Rock showing a trend of lateral thinning and increasingly condensed sedimentation westwards into areas where the oldest of the Chalk Rock Hardgrounds (Ogbourne Hardground) is present. However, apart from local absence of the Glynde Marls Complex near the top of the New Pit Chalk, there is no evidence for the presence of a major erosion event. This questions recent interpretations of microcrinoid data, reportedly showing that the Ogbourne Hardground lithifies a stratigraphical level in the lower part of the New Pit Chalk, with the middle and upper parts of this unit corresponding with a hiatus and related short-lived globally significant sea level fall. Macrofossil biostratigraphy supports the geophysical log interpretations, with evidence of both younger and older parts of the New Pit Chalk below the Ogbourne Hardground. The data are consistent with the Ogbourne Hardground in Wiltshire and Berkshire representing a highly condensed equivalent of thickened nodular chalk fabrics at the base of the Lewes Nodular Chalk in the eastern Chilterns.

1. Introduction

The Chalk Rock comprises a succession of mineralised hardgrounds developed across parts of southern England in the middle and upper Turonian Chalk Group (Fig. 1), described in detail by Bromley and Gale (1982). They can be divided into groups ('suites') that vary in their geographical extent and degree of stratigraphical omission (Bromley and Gale, 1982; Gale, 1996). The hardgrounds are especially well developed close to the eroded margin of the Chalk outcrop, extending eastwards from Dorset, Wiltshire and Berkshire into parts of East Anglia (Bromley and Gale, 1982; Gale, 1996), and the oldest (Ogbourne Hardground) is also seen along the south coast between Dorset and the Isle of Wight (Gale, 1996, 2019a). In more basinal successions, such as the North and South Downs, the equivalent Chalk succession is greatly expanded, and the hardgrounds largely represented by less strongly mineralised omission surfaces and/or intervals of strongly nodular chalk (Gale, 1996; Wood, 1996, fig. 24).

Where present, the hardgrounds typically weather to form a prominent landscape feature that provided a historical basis for recognition of the boundary between the 'Middle Chalk' and 'Upper Chalk' (Bristow et al., 1997). With the later development of a more refined stratigraphy for the Chalk Group (Mortimore, 1986; Mortimore and Pomerol, 1987; Fig. 1), and its application in a modified form by the British Geological Survey (BGS) (Rawson et al., 2001), the Chalk Rock has since been interpreted as equating with a level at or close to the base of the Lewes Nodular Chalk Formation (Bristow et al., 1997; Fig. 1). This correlation has been supported by subsequent field mapping across much of southern England (Bristow et al., 1995, 1999; Hopson et al., 2008; Booth et al., 2010; Aldiss et al., 2012).

Recently, a significantly different interpretation of the age and correlation of the oldest of the Chalk Rock hardgrounds (Ogbourne Hardground) has been presented (Gale, 2019a, fig. 2), building on earlier cyclostratigraphical (Gale, 1996) and geochemical work (Jarvis et al., 2006), that this hardground is related to a significantly older erosion event and short-lived eustatic fall in sea level. In this model, the Ogbourne Hardground lithifies a level significantly below New Pit Marl 1 in the New Pit Chalk, with much of the middle Turonian succession (corresponding with the middle and

* Corresponding author.
E-mail address: maw@bgs.ac.uk (M.A. Woods).

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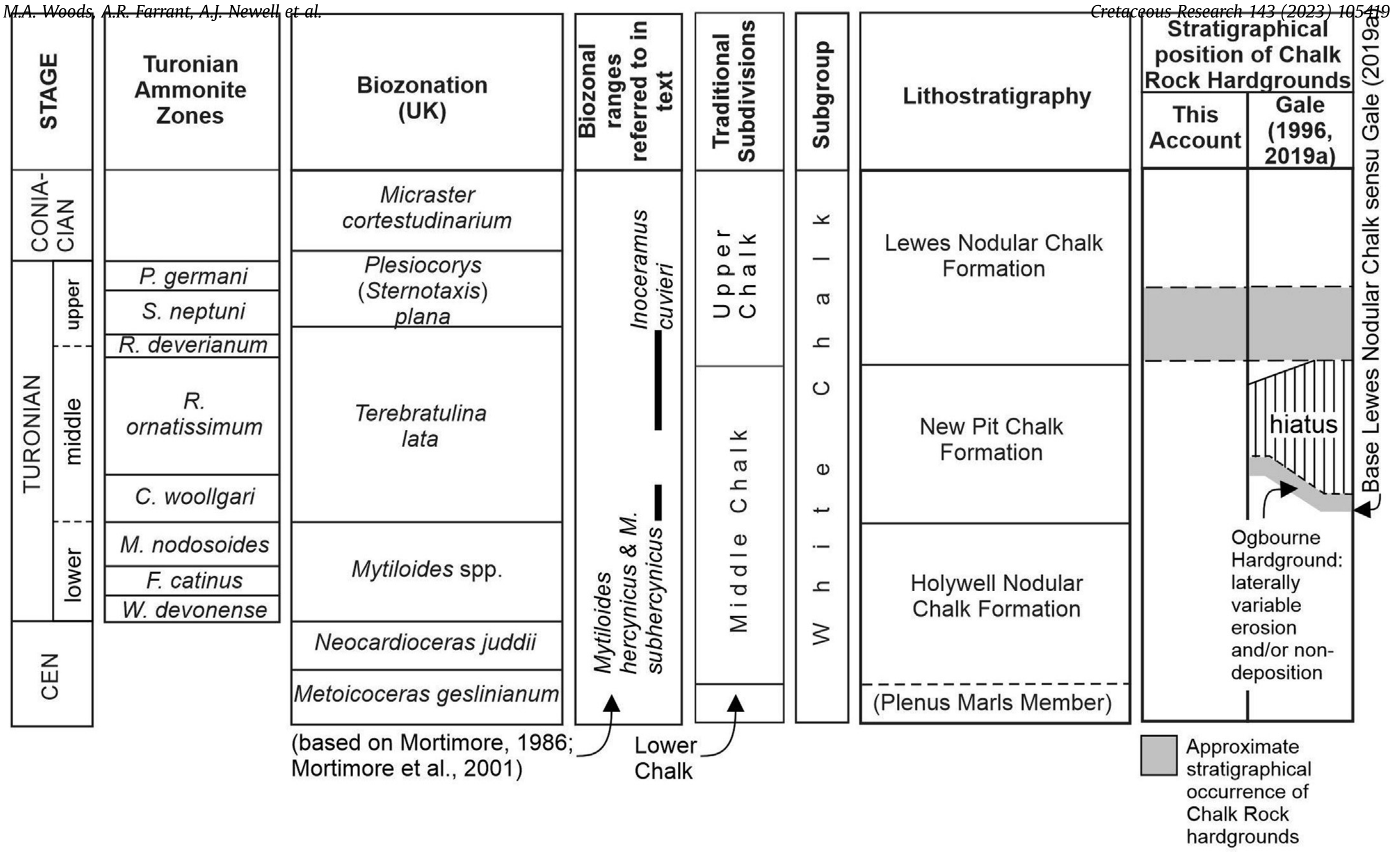

Fig. 1. Upper Cenomanian–Coniacian stratigraphy of the Chalk Group in the Chilterns, showing stratigraphical interpretation of Chalk Rock in the western Chilterns and Dorset of this account and that of Gale (1996, 2019a). In this account, the Ogbourne Hardground is regarded as closely associated with other hardgrounds forming part of the Chalk Rock, and is approximately coincident with the base of the Lewes Nodular Chalk. Gale (1996, 2019a) interpreted the development of the Ogbourne Hardground as a distinctly older event, associated with omission and/or erosion of a significant amount of middle Turonian New Pit Chalk Formation. Turonian ammonite biozonation and positions of lower, middle and upper Turonian follow Gale (2019a, fig. 2). CEN: Cenomanian; W: *Watinoceras*; F: *Fagesia*; M: *Mammites*; C: *Collignoniceras*; R: *Romaniceras*; S: *Subprionocyclus*; P: *Prionocyclus*.

higher parts of the New Pit Chalk Formation; Fig. 1) represented by a hiatus that is coincident with the hardground surface (Gale, 2019a). Novel biostratigraphical data from microcrinoids (Gale, 2019a,b) are used to assert that the broadly synchronous appearance of nodular chalk used by BGS to map the base of the Lewes Nodular Chalk is incorrect (Gale, 2019a). This revised interpretation has been used to suggest new age relationships for correlative hardgrounds on the coast of France (Normandy); to propose a correlation with a variably dated eustatically-related hiatus in Europe, Africa and North America, and to revise the sequence stratigraphy model for mid–late Turonian chalk sedimentation (Gale, 2019a).

Our work explores the stratigraphy associated with the English Chalk Rock succession using a new compilation of high-quality borehole geophysical logs. Unlike conventional lithological logs of outcrop successions, the inflection patterns of geophysical logs are a fingerprint of the continuous record of physical property variation for particular stratigraphical intervals. Thus, similar inflection patterns for stratigraphical intervals that are also constrained between widely developed marker-beds in the Chalk, provide powerful evidence for correlation. Our new borehole data are selected using maps of the distribution of Chalk Rock hardgrounds produced by Bromley and Gale (1982) and Gale (1996) to span regions where the Ogbourne Hardground is present and areas where it is absent. Any major hiatus in the New Pit Chalk associated with the Ogbourne Hardground ought to be recognisable by the lateral absence of the geophysical log signature for the middle and higher parts of the New Pit Chalk. We also assess the large archive of BGS biostratigraphical data obtained from logged successions where the New Pit Chalk has been identified below the Ogbourne Hardground, and from New Pit Chalk where the regional development of the Ogbourne Hardground can be confidently inferred.

2. Methodology

Borehole geophysical logs provide a means of interpreting the subsurface lithostratigraphy of the Chalk Group (Mortimore, 1986; Mortimore and Pomerol, 1987; Woods and Aldiss, 2004; Woods, 2006a; Woods and Chacksfield, 2012), and this has formed the basis for developing 3D regional digital geological models (Woods, 2015; Woods et al., 2016). Typically, marls correspond with high gamma and low resistivity log values, forming sharply defined inflections. On resistivity logs, hardgrounds correspond with sharply increased values, or sharply reduced interval transit times on sonic logs. The concentration of some iron (e.g. glauconite) and phosphate minerals at hardgrounds typically causes hardgrounds, like marls, to correspond with peaks on gamma logs, but they can be discriminated by their contrasting resistivity/sonic response. Calibration of geophysical logs is achieved through direct correlation of borehole core and related geophysical log data and/or by reliable comparison with nearby outcrop successions, and practice shows that the patterns of signatures, at least from the Cenomanian to lower Coniacian, are remarkably persistent regionally (Woods, 2006a). Increasingly, borehole image logs are used as a cost-effective means of providing evidence of changes in rock physical properties to which geophysical log signatures can be related, and this has proved helpful in parts of the Berkshire Downs and Wiltshire for understanding the stratigraphy of the Chalk Rock (e.g. Banterwick Barn Borehole; Murphy, 1998; Murphy et al., 1997; Pearce et al., 2003; Woods and Aldiss, 2004).

For this work, we have selected geophysical logs from the BGS archive that allow interpretation of the pattern of stratigraphical development below the Chalk Rock for an area of the Chilterns extending between Hertfordshire, north of London, south-westwards towards Salisbury in Wiltshire (Fig. 2). This study is guided by the regional maps of Chalk Rock hardground distribution produced by Bromley and Gale (1982), Gale (1996) and Gale (2019a), to ensure that our correlation line spans the boundary separating areas where the Ogbourne Hardground is present and areas where it is absent (Fig. 2). Stratigraphical control for our correlations is provided by the cored and geophysically logged Banterwick Barn No. 2 Borehole, and by the published interpretation and correlation of the Thundridge Borehole with the cored and geophysically logged BGS Fetcham Mill Borehole near Leatherhead, a regional standard for interpretation of geophysical logs in the London Basin (Murray, 1986; Mortimore and Pomerol, 1987; Woods, 2006a). We have also collated biostratigraphical data from the extensive BGS field mapping programme conducted in the last 20 years. These data have only partly been summarised in relevant BGS publications (e.g. Hopson et al., 2008; Booth et al., 2010).

The Turonian stratigraphy, geochemistry and palynology of one of our control boreholes (Banterwick Barn) has been extensively investigated by other workers (Murphy et al., 1997; Murphy, 1998; Pearce et al., 2003; Woods and Aldiss, 2004; Jarvis et al., 2006). However, re-analysis of the original published work on this borehole (Murphy et al., 1997; Murphy, 1998; Pearce et al., 2003) suggests that the basis for identification of named markers for part of the Turonian marl seam succession may need to be reconsidered. Murphy et al. (1997) only recognised a formational interpretation of the Banterwick succession, and Pearce et al. (2003), who annotated the borehole core log with the horizons of marl seams named by Gale (1996) in his UK review of Turonian stratigraphy, commented that “In the absence of good macrofossil biostratigraphic control to determine the stratigraphic position of the core material,

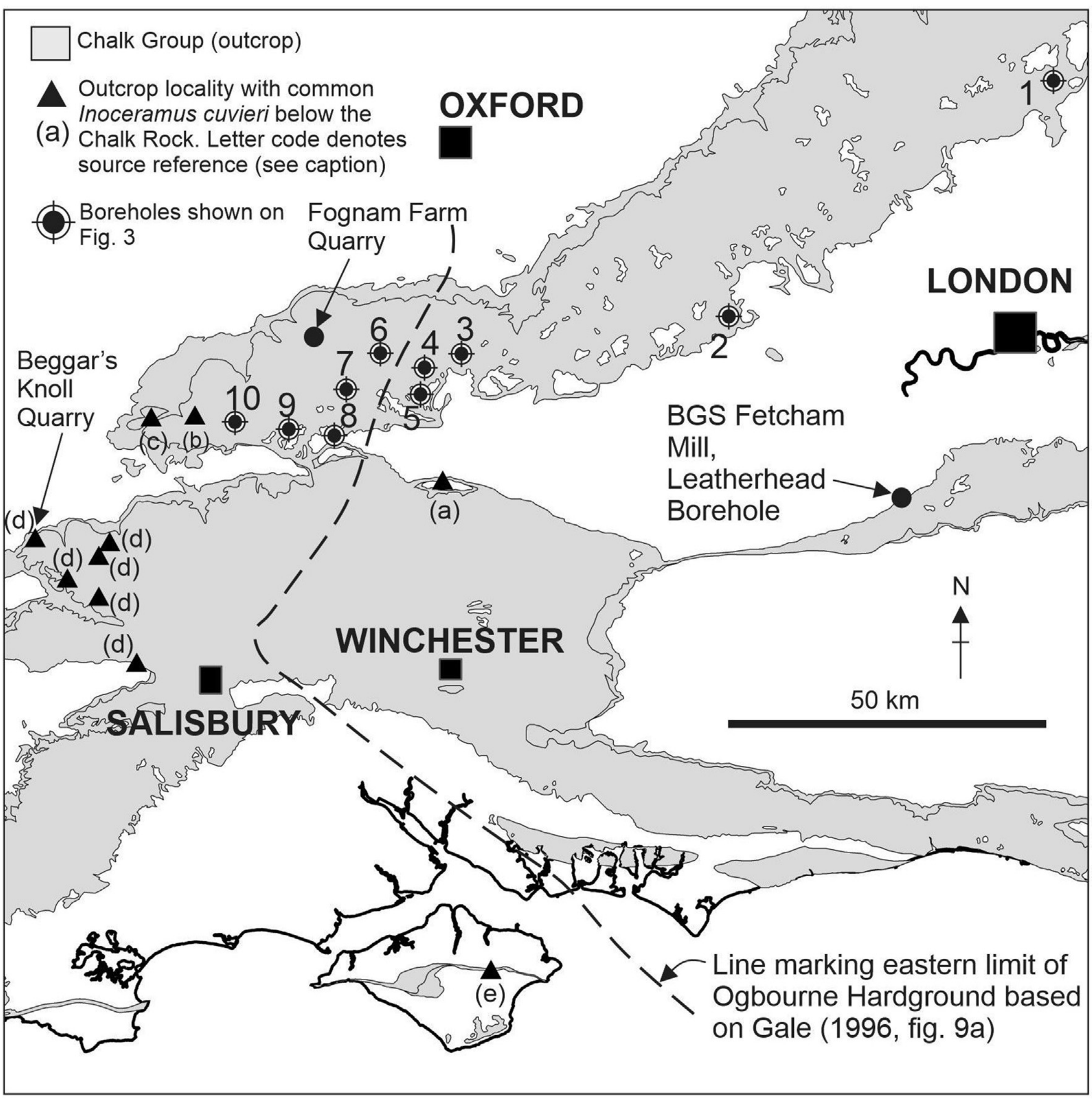

Fig. 2. Distribution of the Ogbourne Hardground and location of key boreholes and sites with biostratigraphical data. References for sources of biostratigraphical data: (a) = Woods (2006b); (b) = Woods (2011), (c) = Woods (2010); (d) = Woods (2004); (e) = Woods (2007).

lithostratigraphic criteria were used"; and further, "The positions of traditional macrofossil zones in the Banterwick Barn succession were estimated based on lithostratigraphic criteria." Presumably 'lithostratigraphical criteria' means comparison of the logged Banterwick succession with nearby outcrop successions, for example those described by Gale (1996). For the Banterwick Borehole, the most likely outcrop analogue for comparison of its stratigraphy is Fognam Farm Quarry (Gale, 1996, fig. 5), but as discussed by Mortimore et al. (2001) there are potential problems with how Gale (1996) interpreted the succession below the base of the Chalk Rock at this locality, with biostratigraphical and nearby borehole evidence suggesting a significantly higher stratigraphical level in the New Pit Chalk below the base of the Chalk Rock. Gale's (1996) cyclostratigraphical scheme that guided the interpretation of Fognam Farm Quarry, and possibly also the later interpretation of the Banterwick Barn Borehole, is based on recognition and correlation of rhythmically deposited sedimentary packages of chalk and marl (couplets) between widely separated outcrops across southern England, and assigning each couplet a unique alphanumeric number (F1, F2 etc for the equivalent of the New Pit Chalk Formation). However, Gale (1996, fig. 5) illustrated huge variability in the extent of development of marl seams between adjacent sections in the New Pit Chalk (Gale, 1996, fig. 5). The relatively few controls on this correlation was a criticism of this Turonian cyclostratigraphical scheme (Gale, 2019a). For example, although ammonites are widely recognised in Turonian successions, they are common at few horizons in UK Chalk Group successions (Gale, 1996).

Whilst geochemical correlations of marl seams between Sussex/Kent, Yorkshire and Germany (Wray, 1999) has established a broad framework of markers to guide lithostratigraphical correlations, the stratigraphical coverage and resolution of this framework are not adequate to guide decisions about the correlation of units that are the focus of this work. Consequently, there is much greater scope for how marl seams are interpreted and correlated between sections; the cutting out of marl seams illustrated by Gale (1996, fig. 5) at Fognam Farm is not at all certain, and appears to be based on a comparison with Beggar's Knoll Quarry in Wiltshire (Gale, 1996, fig. 5) for which we also present new data herein. To solve this stratigraphical problem, our work increases the confidence of correlation by using a closely spaced network of borehole geophysical logs, to link distinctive geophysical log inflection patterns in the Banterwick Borehole to the Thundridge Borehole (Murray, 1986; Mortimore and Pomerol, 1987), and further to the cored BGS Fetcham Mill Borehole at Leatherhead, which serves as a regional reference for Chalk Group stratigraphy (Mortimore, 1986; Mortimore and Pomerol, 1987; Mortimore et al., 2001). The results of this methodology, discussed below, update the previous correlation of the New Pit Chalk in the Banterwick Borehole described by Woods and Aldiss (2004).

3. Results

Fig. 3 shows a correlation of borehole resistivity logs at 10 sites between Thundridge in Hertfordshire, and Marlborough in Wiltshire. All logs, apart from Taplow, include the Plenus Marls close to their base, and extend upwards into the Lewes/Seaford Chalk Formation. On Fig. 3, the Chalk Rock is clearly identified as a high resistivity spike, and is used to define the top of a shaded region on the correlation panels that extends down to the top of the Glynde Marls Complex (see below). This shaded area shows the pattern of lateral stratigraphical change between the highest of the Chalk Rock hardgrounds (Hitch Wood Hardground of Bromley and Gale, 1982) and the base of the Lewes Nodular Chalk Formation. In the eastern Chilterns, the base of the Lewes Nodular Chalk in the Thundridge Borehole is interpreted to occur within the interval of increasing resistivity that is located immediately above a broad low resistivity inflection (Fig. 3). Previous work provides strong evidence for correlation of this low resistivity inflection with the Glynde Marls Complex (Wood, 1986; Mortimore and Pomerol, 1987; Woods, 2006a) based on close comparison with the cored and geophysically logged Fetcham Mill Borehole (Leatherhead, Surrey; Figs 2, 4), a regional standard for interpretation of borehole geophysical logs in the Chalk Group of the London Basin.

Westwards, the base of the Lewes Nodular Chalk becomes approximately coincident with the base of the high resistivity inflection formed by the Chalk Rock. This likely reflects the combined strengthening and addition of hardgrounds westwards described by Bromley and Gale (1982), causing the basal part of the Lewes Chalk shown on Fig. 3 to become increasingly condensed, graphically shown by the significant thinning of the shaded area above the Glynde Marls Complex. In the Thundridge succession, the large low resistivity spike between the base of the Lewes Nodular Chalk and the Chalk Rock represents Southerham Marl 1 (Wood, 1986; Mortimore and Pomerol, 1987). This marl generally equates with the Fognam Marl at most localities described by Bromley and Gale (1982), except locally (e.g. Ewelme, Oxfordshire) where this name has also been applied to the equivalent of the Glynde Marl (Gale, 1996; Woods and Aldiss, 2004). The inflection formed by this marl is traceable westwards into the Chalk Rock succession, although its amplitude significantly diminishes.

The New Pit Chalk Formation typically forms a broad interval of generally low resistivity chalk, punctuated by a series of sharp low resistivity inflections that correspond with marl seams in borehole core (Woods, 2006a), and this is clearly seen in Figs. 3 and 4. The base of the New Pit Chalk is marked by the downward transition into high resistivity chalk representing the much more strongly cemented Holywell Nodular Chalk Formation, typically with a less strongly serrated resistivity log signature. The boundary itself corresponds with a low resistivity inflection that sits on a shoulder of higher resistivity values, identified in the Banterwick Borehole as the Lulworth Marl (Pearce et al., 2003) or correlative Gun Gardens Main Marl (Woods and Aldiss, 2004). A distinctive peak in the middle of the Holywell Nodular Chalk ('P') in the cored Banterwick Borehole, corresponding with an interval of coarser-grained, shell-rich chalk with common *Mytiloides* (Murphy et al., 1997, fig. 2; Pearce et al., 2003, fig. 3), can be traced into all other boreholes, and this provides a guide to the consistency of our interpretation of the base of the New Pit Chalk Formation. The Plenus Marls, at the base of the Holywell Nodular Chalk, forms a very consistent and sharply developed low resistivity inflection, formed by the clay-dominated lithologies that characterise this unit.

The most distinctive geophysical features within the New Pit Chalk Formation are a pair of geophysical log inflections ('B', 'C') that can be traced through all borehole logs on Fig. 3. These markers maintain a similar relative spacing, but with a slight thinning westwards. The markers are sharply defined low-resistivity inflections that correspond with marl seams seen in the Banterwick Barn No. 2 Borehole core. The higher of these two inflections ('C') is used as a correlation datum for comparing the log responses in Fig. 3 up to the base of the Lewes Nodular Chalk, shaded in Fig. 3 to highlight lateral changes in its stratigraphy. This interval, like the shaded interval at the base of the Lewes Nodular Chalk, shows a pattern of progressive thinning westwards. The pattern of inflections that form part of the shaded interval in the top of the New Pit Chalk is very distinct and can be traced (dotted lines) with a high degree of confidence between the boreholes. Vertical bars just above 'C' denote the vertical coverage of a particularly distinctive interval ('D') of geophysical log signature that can be identified in all the boreholes. This interval is relatively expanded in the Thundridge Borehole, where it is capped by the Glynde Marls Complex,

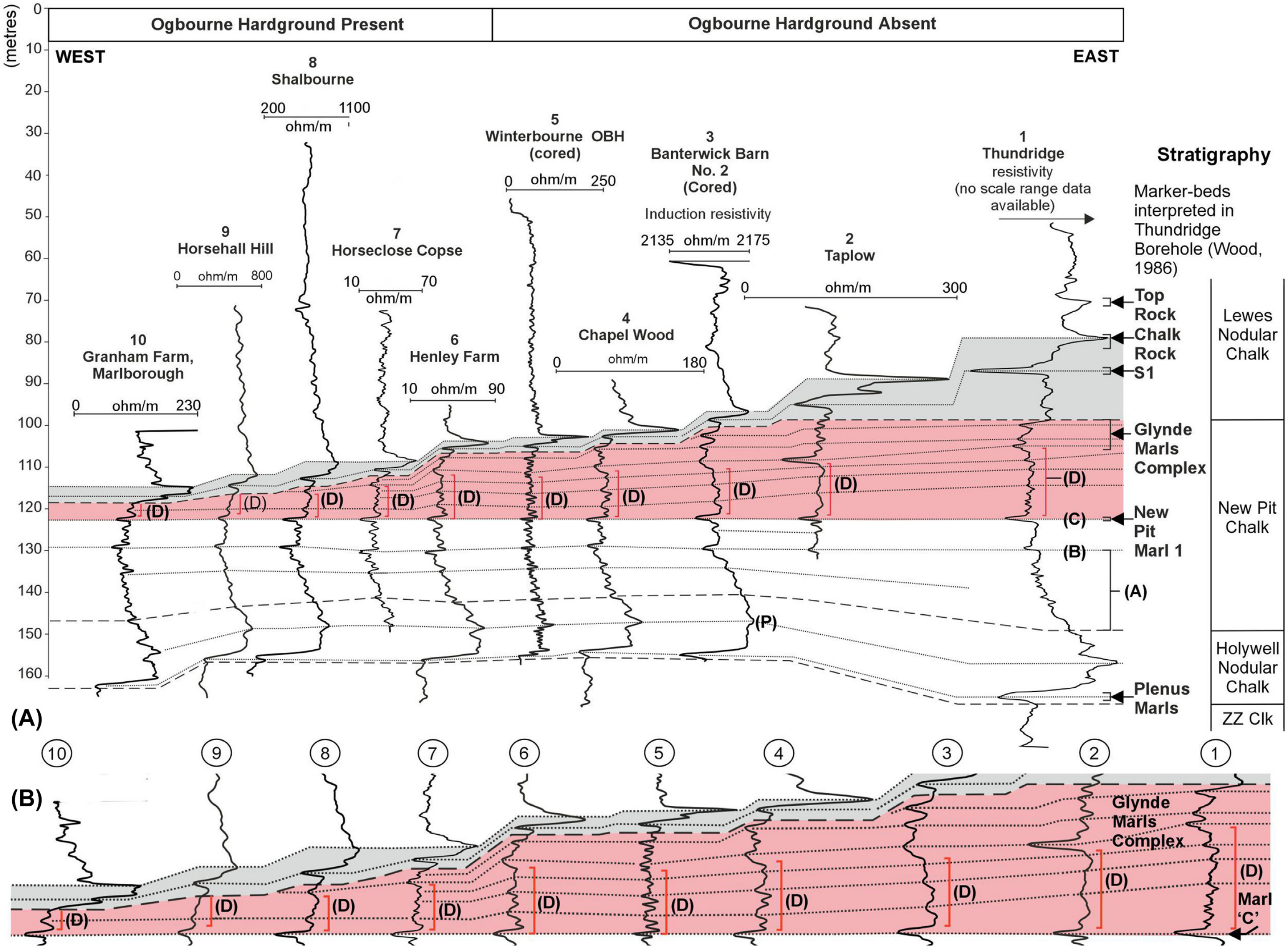

Fig. 3. Correlation of borehole resistivity logs in the Chalk Group across the Chilterns between areas where the Ogbourne Hardground is absent (east) and areas where this unit is present (west). (A) Overview correlation showing westward thinning of intervals in the upper New Pit Chalk (shaded) and basal Lewes Nodular Chalk (shaded); (B) detailed view of inflection pattern correlation above Marl C, showing thinning rather than erosion of interval 'D' below the Glynde Marls Complex as it is traced westwards across the Chilterns. The Glynde Marls Complex appears to be the only part of the New Pit Chalk that is completely removed by erosion associated with the Ogbourne Hardground. S1: Southerham Marl 1; ZZ Clk: Zig Zag Chalk.

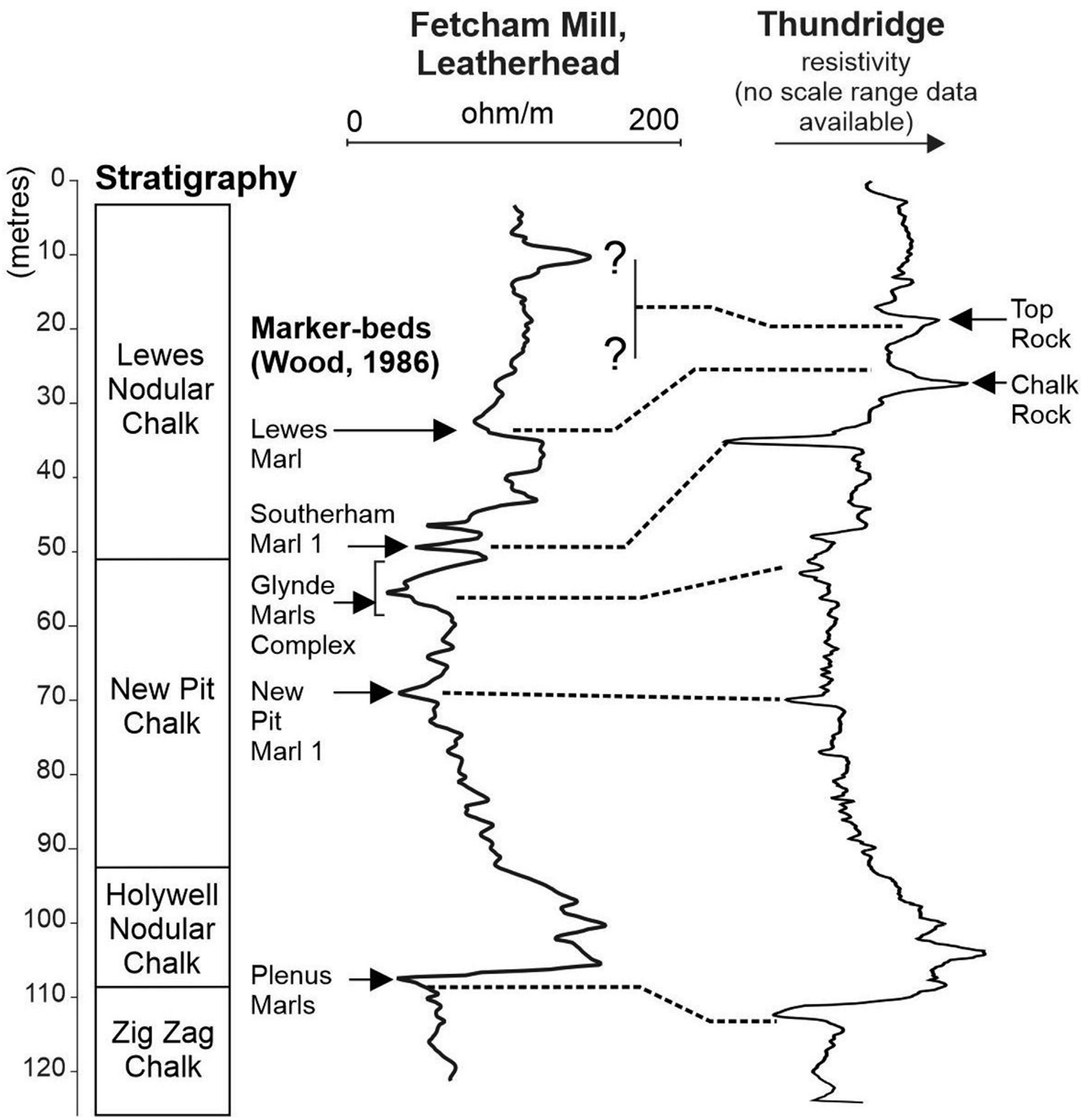

Fig. 4. Correlation and stratigraphical interpretation of borehole resistivity logs in the cored Fetcham Mill (Leatherhead) Borehole and the Thundridge Borehole.

but westwards the marl seam inflections that Interval D contains become more closely spaced and diminish in amplitude, and the correlative of the Glynde Marls Complex thins and completely disappears in the Horsehall Hill and Marlborough boreholes.

4. Discussion

Fig. 3 provides evidence for increasingly condensed sedimentation and local erosion of the New Pit Chalk westwards between marl ‘C’ and the base of the Lewes Nodular Chalk. Recognition of the Glynde Marls Complex in the top of this interval indicates that it correlates stratigraphically with the upper part of the New Pit Chalk (Figs. 3, 4). This pattern of thinning of the upper New Pit Chalk is matched by the westward thinning associated with the overlying basal part of the Lewes Nodular Chalk. Maps of the hardgrounds (Gale, 1996, fig. 9a) that comprise the Chalk Rock show that the Ogbourne Hardground can be inferred to form part of the Chalk Rock succession in the Henley Farm Borehole (Berkshire) and sites further west (Fig. 2). Thus, the Ogbourne Hardground is developed above a thinned and condensed interval of stratigraphy that microcrinoid data (Gale, 2019a) purport to be omitted above this hardground surface. Westward thinning of the upper New Pit Chalk is restricted to the interval above marl 'C', which in the Thundridge Borehole is identified as the New Pit Marl 1 (Wood, 1986; Mortimore and Pomerol, 1987). Woods and Aldiss (2004) designated marls 'B' and 'C' the 'marker marls' in the Banterwick and correlative boreholes, and based on their relatively close proximity to the base of the New Pit Chalk, suggested that they were probably below the level of the New Pit Marls. The correlation shown on Fig. 3 changes the context of this interpretation by revealing a sharp lateral thinning in the lower part of the New Pit Chalk ('A') between Thundridge and sites further west. Thus, whilst the 'marker marls' at Banterwick might appear relatively low down in the stratigraphy of the New Pit Chalk, the new correlation suggests that they are likely to be relatively higher in the stratigraphy of the New Pit Chalk, with marker marl 'C' likely representing New Pit Marl 1. However, irrespective of the actual identity of the marl inflections 'B' and 'C', the context of these markers with respect to the Glynde Marls Complex in Fig. 3 provides strong evidence for the presence of upper New Pit Chalk above Marl 'C', and its lateral development westwards as a thin and condensed succession below the Ogbourne Hardground. Both Woods and Aldiss (2004, fig. 6) and Gale (2019a) recorded pronounced local thinning of the upper New Pit Chalk in the eastern Chilterns where the Ogbourne Hardground is absent, bringing New Pit Marl 2 to within a few metres of the base of the Chalk Rock (Gale, 2019a, fig. 6), but this is a local axis of thinning centred on the Goring Gap with its maximum development at Henley and Ewelme (Oxfordshire).

The presence of thin and condensed upper New Pit Chalk below the Ogbourne Hardground is consistent with field and borehole biostratigraphical evidence. At Fognam Farm [SU 296 893] (Fig. 2), where a relatively weak development of the Ogbourne Hardground occurs (Bromley and Gale, 1982), the bivalve *Inoceramus cuvieri* is abundant in the chalk a short distance below the hardground. This bivalve, whilst quite broadly ranging in the New Pit Chalk, is characteristically common in the upper New Pit Chalk at and above the New Pit Marls (Mortimore, 1986). *Inoceramus cuvieri* is also common in exposures of New Pit Chalk further west in areas where the Ogbourne Hardground is more strongly developed than at Fognam Farm, including: Steeple Langford [SU 04530 37406], Baverstock [SU 0376 3226], Chitterne [ST 98197 41936] (Woods, 2004), and Morgan's Hill [SU 03276 67437] (Woods, 2010b) (Fig. 2). At Beggar's Knoll Quarry [SU 8890 5054] (Fig. 2) described by Gale (1996, 2019a), and where there is semi-continuous exposure of the succession below the Ogbourne Hardground, *Mytiloides* ex gr. *hercynicus/subhercynicus* (characteristic of the basal/lower part of the New Pit Chalk) occurs in the 3 m interval above the contact with the Holywell Nodular Chalk, and *Inoceramus cuvieri* dominates higher in the New Pit Chalk succession (Woods, 2004). Here, the lithological log of the Ogbourne Hardground and underlying marls seams recorded in 2004 (Woods, 2004, fig. 1) compares very closely with the spacing of the hardground and marker marls 'B' and 'C' on the geophysical log at Granham Farm, Marlborough, nearly 30 km NE of Beggar's Knoll (Fig. 5). In the Marlborough district, New Pit Chalk immediately below the Ogbourne Hardground contains *Inoceramus cuvieri* and the foraminifer *Labyrinthidoma* (= *Coskinophragma*) (Woods, 2010b), the latter typically associated with common *I. cuvieri* in the higher part of the New Pit Chalk (Mortimore, 1986; Mortimore and Wood, 1986).

In Dorset, Bristow et al. (1995) identified the New Pit Marls in the succession below the Spurious Chalk Rock (= Ogbourne Hardground) at Shillingstone Hill, and the section published by Mortimore et al. (2001) shows the presence of *Mytiloides subhercynicus*? in the lower part, and abundant *I. cuvieri* with *Labyrinthidoma* in the upper part of the succession. Whilst the records of

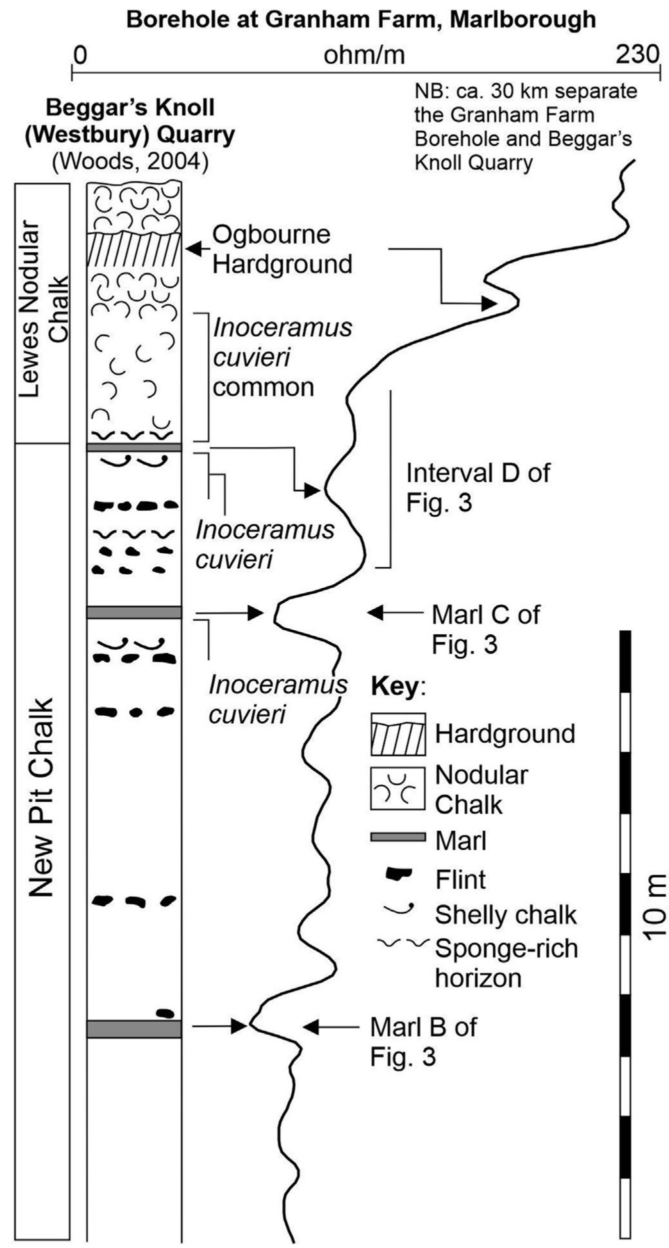

Fig. 5. Lithological log of the Ogbourne Hardground and immediately underlying New Pit Chalk succession at Beggar's Knoll Quarry [SU 8890 5054], Wiltshire, recorded in 2004 (Woods, 2004), with key biostratigraphical records and comparison with inflection patterns on the resistivity log for the borehole at Granham Farm, Marlborough shown in Fig. 3.

common *Inoceramus cuvieri* and *Labyrinthidoma* are not definitive evidence for the upper New Pit Chalk, they are consistently developed associations below the Ogbourne Hardground at a number of localities, and are also biostratigraphically consistent with the geophysical log correlations presented in Fig. 3 for the presence of condensed upper New Pit Chalk Formation below the Ogbourne Hardground. The general conclusion reached by consideration of these faunal data, is that both older and younger parts of the New Pit Chalk are present below the Chalk Rock in areas where the Ogbourne Hardground is identified as forming the oldest part of the Chalk Rock succession.

Independent verification of our geophysical log correlation using the published micro-fossil and geochemical data for the

Banterwick Borehole is compromised by these schemes likely being tied to indirect interpretations of marl-seam stratigraphy by comparison with published sections, that in turn depend on a cyclostratigraphical model (Gale, 1996) with greater scope for alternative interpretation (see 1 above). Using the $\delta^{13}C$ curves for other UK sites (Jarvis et al., 2006) to interpret the stratigraphy in the Banterwick Borehole is also problematic because each site is radically different in terms of its depositional history and thickness of strata (Norfolk, Berkshire, Kent), and the mid–late Turonian $\delta^{13}C$ curve is relatively featureless, limiting the ability to precisely define individual marl seams. However, it is notable that in the Dover, Trunch and Culver successions, the broad peak on the $\delta^{13}C$ curve coincident with the Round Down Event is not underlain by peaks of any equivalent or greater amplitude until below the Lulworth Event, but this is not true for the Round Down Event in the Banterwick Borehole succession (Jarvis et al., 2006, figs. 6, 7). Potentially, the $\delta^{13}C$ peak for the Round Down Event could be lower down in the Banterwick Barn succession. Foraminiferal data for the Banterwick Borehole are low resolution and zonal boundaries are poorly constrained (Murphy, 1998, p. 164), and marker-marl interpretations on geophysical log correlations of the Banterwick Borehole (Murphy, 1998, p. 201) appear to be based on comparison with published accounts of regional Chalk Group stratigraphy (caption text for figure 6.5 of Murphy, 1998) by Mortimore (1986) and Gale (1996), rather than consideration of the characteristic patterns of geophysical log inflections.

Setting aside the identity of all of the marl seams that we discuss in this paper, and the biostratigraphical evidence that we present, one powerful conclusion of the geophysical log correlation shown on Fig. 3 is that there is no evidence for a major hiatus in stratigraphy in the higher part of the New Pit Chalk in areas where the Ogbourne Hardground is present in the south-west compared to areas where it is absent in the north-east. The evidence presented by this figure is for the succession to become progressively condensed in its upper part towards the south-west. This is inconsistent with the conclusions of Gale (2019a) despite what microcrinoid data are purported to show.

Given the strength of the geophysical and biostratigraphical data, it is not entirely clear how the apparently contradictory results for the age of the Ogbourne Hardground provided by analysis of microcrinoids (Gale, 2019a) can be reconciled. The published sample horizons on which the microcrinoid age of the Ogbourne Hardground is based (Gale, 2019a, Appendix A, figs 1 – 3; 6, 7) suggest that, at least in part, these samples might actually provide evidence of a trend of increasingly condensed and/or winnowed sediment in the top of the New Pit Chalk, across which the Ogbourne Hardground later developed as a broadly synchronous event. It is also possible that palaeoecological factors might complicate understanding of the stratigraphical ranges of key taxa in a condensed shelf environment compared to an expanded basin setting. Ferré et al. (2018) noted that caution was needed in using roveacrinids (the group of microcrinoids used to study Chalk Rock stratigraphy) to establish correlations. Wider use and adoption of microcrinoid biostratigraphy will likely reveal which forms are the most reliable for stratigraphical interpretation.

5. Conclusion

Geophysical logs that can be related to cored boreholes show evidence below the Chalk Rock of thinning and condensed sedimentation westwards in the higher part of the New Pit Chalk between Hertfordshire and Wiltshire, most probably affecting the interval above New Pit Marl 1. There is no evidence from geophysical logs for the Ogbourne Hardground representing lithification of a relatively low horizon in the New Pit Chalk, or for the higher parts of the formation being omitted at a hiatus coincident with the hardground surface. Thinning of the succession below the Ogbourne Hardground parallels westward thinning of the basal Lewes Nodular Chalk, associated with strengthening of the main hardground suites that comprise the Chalk Rock. This suggests that the stratigraphical affinity of the Ogbourne Hardground is with the base of the Lewes Nodular Chalk rather than with a level low in the New Pit Chalk.

Biostratigraphical data collected during the course of systematic mapping of the Chalk Group over the last 20 years confirms that the New Pit Chalk succession developed below the Ogbourne Hardground contains evidence for both the lower part of the formation (the bivalve *Mytiloides* ex gr. *hercynicus*/*subhercynicus*) and upper part (common records of the bivalve *Inoceramus cuvieri* and the foraminifer *Labyrinthydoma*). These observations validate the criteria adopted by the BGS to map the base of the Lewes Nodular Chalk. Recently published microcrinoid data seem likely to provide an indication of lateral attenuation and sediment winnowing in the top of the New Pit Chalk, rather than providing evidence for a significant hiatus and associated erosion of the middle and upper parts of this formation.

Data availability

Data will be made available on request.

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