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Review paper

Applied palaeontology in the Chalk Group: quality control for geological mapping and modelling and revealing new understanding

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ABSTRACT

The Chalk is a major aquifer, source of raw material for cement and agricultural lime, and a host geological unit for major civil engineering projects. Detailed understanding of its development and lateral variation is significant for our prosperity and for understanding the potential risks of pollution and groundwater flooding, and in this aspect palaeontology plays a central part. Historically, the distribution of macrofossils offered important refinement to the simple three-fold subdivision of the Chalk based on lithological criteria. In recent decades, the advent of a more sophisticated lithostratigraphy for the Chalk, more closely linked to variations in its physical properties, provided an impetus for the British Geological Survey to depict this on its geological maps. Tracing Chalk stratigraphical units away from the well-exposed successions on which the new stratigraphy is based requires subtle interpretation of landscape features, and raises the need for methods of ensuring that the interpretations are correct. New and archived palaeontological data from the vast BGS collections, interpreted as a component of a broad-based holostratigraphical scheme for the Chalk, and spatially analysed using modern Geographical Information Systems (GIS) and landscape visualisation technology, helps fulfil this need. The value of palaeontological data in the Chalk has been boosted by the work that underpins the new lithostratigraphy; it has revealed broad patterns of biofacies based on a range of taxa that is far more diverse than those traditionally used for biostratigraphy, and has provided a detailed reference framework of marker-beds so that fossil ranges can be better understood.

In the subsurface, biofacies data in conjunction with lithological and geophysical data, has been used to interpret and extrapolate the distribution of Chalk formations in boreholes across southern England, allowing development of sophisticated three-dimensional models of the Chalk; revealing the influence of ancient structures on Chalk depositional architecture, and pointing to palaeoenvironmental factors that locally affected productivity of Chalk in Late Cretaceous oceans.

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1. Introduction

Geology is now widely recognised as vital to our economic prosperity. It provides us with raw materials for manufacturing, sources of water and energy, and provides foundations for our infrastructure. The Chalk has a wide outcrop across the densely populated area of south-east England, and is peppered with boreholes for water supply; quarried for cement and agricultural lime, and hosts many large scale civil engineering structures, such as the Channel Tunnel. Understanding variation in the thickness and distribution of the Chalk, and how its physical properties vary, are vital requirements for future economic and population development across southern England, and fossils play an important part in delivering this understanding.

Historically, fossils have always had an important role in Chalk geology. The substantial thickness and apparent physical uniformity of the Chalk presented early workers with the problem of how to subdivide it on geological maps. The simple three-fold classification into Lower, Middle and Upper Chalk that became the traditional classification, defined at feature-forming beds of hard chalk, persisted into the latter part of the twentieth century, but presented problems for detailed understanding of internal variation. In contrast, macrofossils appeared to provide a basis for detailed subdivision of outcropping Chalk successions that could better describe its spatial distribution and age relationships, and regional biozonal maps were published for the Chalk by Brydone (1912), Gaster (1924, 1929, 1932, 1937, 1941, 1944), Young (1905, 1908), Hewitt (1924, 1935) and Peake and Hancock (1970). Some historical accounts even described units containing particular fossil assemblages as if they were distinct lithological entities; for example, use of the term 'Marsupites Chalk' by Dines and Edmunds (1929) in the Geological Survey Memoir for Aldershot and Guildford. As outlined by Gale and Cleevely (1989), this fixation on palaeontology by early Chalk workers stemmed largely from the highly influential publications of Arthur Rowe. In his description of coastal sections (Rowe, 1900, 1901, 1903, 1904, 1908), Rowe emphasised the value of fossils for subdividing the Chalk and often criticised the use of lithological criteria. The position of fossils at the heart of Chalk geology was further bolstered by confusion of some of the marker-beds used to recognise the traditional units, and observed inconsistencies in the stratigraphical horizons of these markers (Jukes-Browne, 1880; Rowe, 1901, 1908).

The last 30 years, spurred on by economic imperatives requiring a better understanding of variation in the Chalk's physical properties, has seen a revolution in the geology of the Chalk, including the advent of a detailed national lithostratigraphical scheme (Rawson et al., 2001; Hopson, 2005) recognised across southern England on recent British Geological Survey (BGS) maps. Whilst this new Chalk classification emphasises differences in physical character that are of particular value to engineers and hydrogeologists, the exhaustive work on outcrop sections that has been required to produce it has revealed important relationships between macrofossils and lithostratigraphy. With a robust scheme of Chalk formations, defined by surfaces or marker-beds that in many cases are the products of basin-wide events, it has become easier to understand broad patterns of macrofossil occurrences. This new understanding of the palaeontology of the Chalk, and the adoption of a *holostratigraphical* approach which integrates different kinds of geological data to arrive at best-fit interpretations, has proved invaluable for helping to understand the surface distribution of different units of Chalk in poorly exposed terrain, and in tracing the distribution of these units in the subsurface for geological modelling.

This work shows how macrofossil palaeontology remains a valuable tool in our understanding of the distribution, correlation and basin structure of the Chalk Group, not in spite of lithostratigraphy, but because of it.

2. Biostratigraphy in the context of Chalk Group holostratigraphy

Between 1999 and 2006, the BGS released digital reports describing the holostratigraphy of the Upper Silurian Ludlow Series (Molyneux, 1999; http://www.bgs.ac.uk/reference/holostrat/ludlow.html) and the Lower Cretaceous Albian Stage (Wilkinson, 2006; http://www.bgs.ac.uk/reference/holostrat/albian.html), and a manuscript was prepared for the Chalk Group,

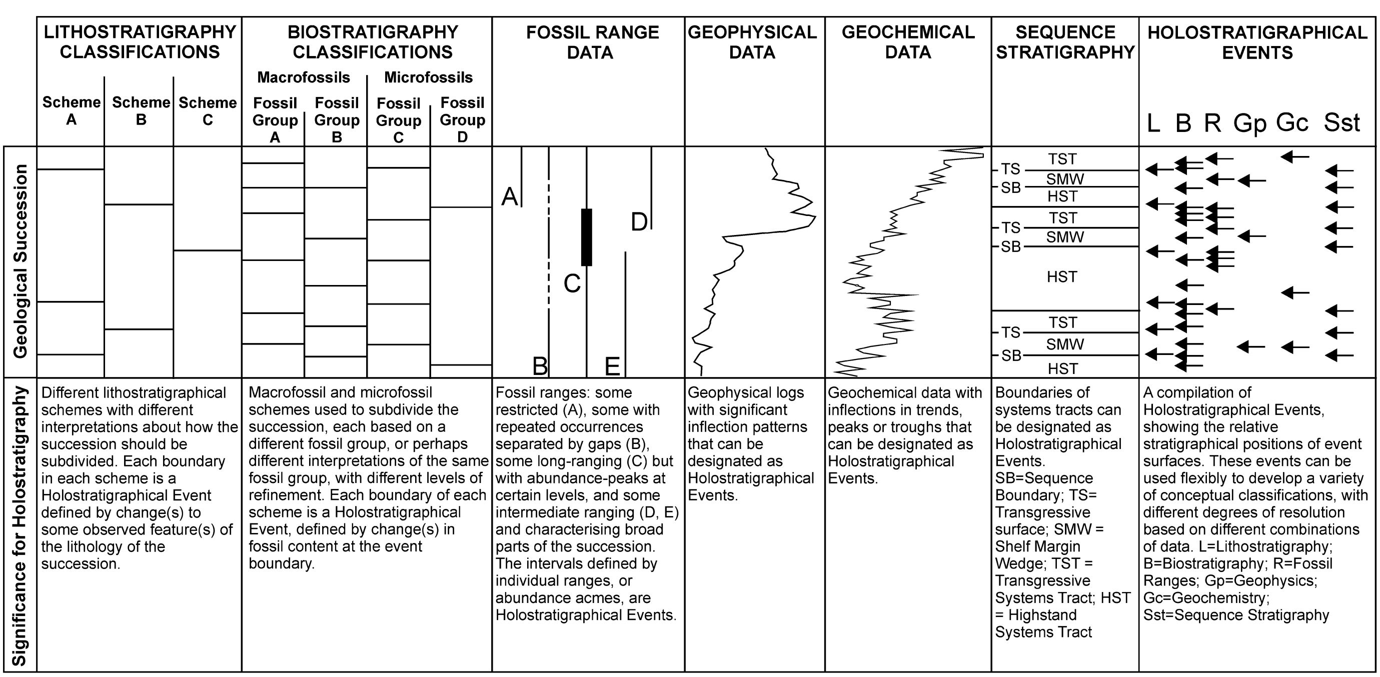

Fig. 1. Examples of data types and their use in Holostratigraphy.

but remains unpublished. As applied in these reports, and outlined by Rawson et al. (2002), Holostratigraphy refers to the 'total stratigraphy' of a given interval. Its aim is to understand the inter-relationships between all the different stratigraphical events that can potentially occur in a succession, and summarise these in a *conceptual* stratigraphical log. These events can be defined by any number of features including, for example, lithostratigraphy, biostratigraphy, chronostratigraphy, cyclostratigraphy, and geochemistry. The Holostratigraphy scheme can include all competing views on how a succession might be sub-divided, the only important aspect in compiling the conceptual Holostratigraphy is to understand the relative positions of these events (Fig. 1). More recently, Hampton et al. (2010) adopted a holostratigraphical approach to understand the Chalk of the North Sea Eldfisk Field

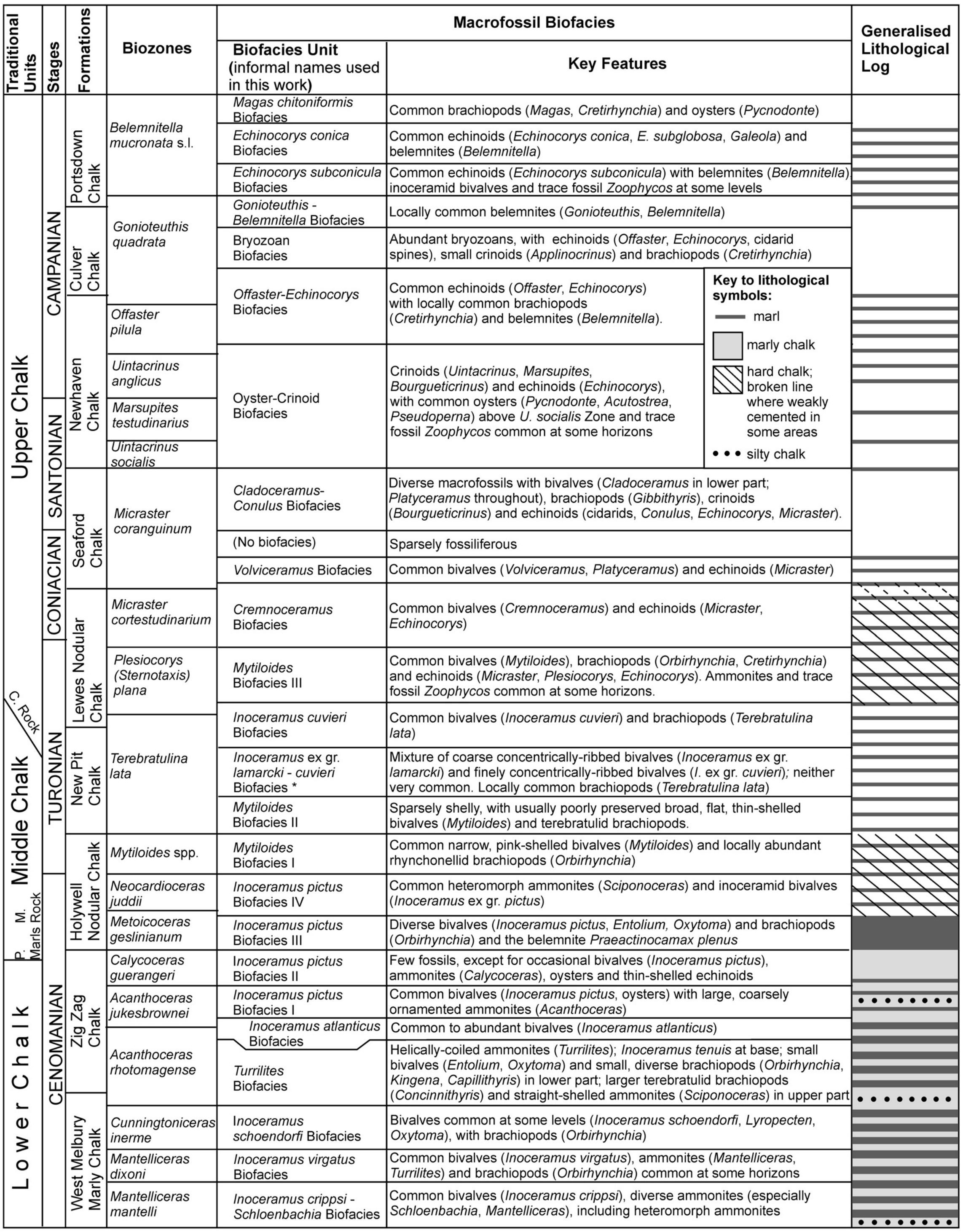

Fig. 2. Stratigraphy of the Chalk Group with description of macrofossil biofacies units. Scheme and nomenclature for biofacies units is informal, and based on a compilation of BGS field data and published records relating to the Chalk of southern England. Lithostratigraphy is generalised and not intended to illustrate detailed relationships of fauna and lithology. Taxa listed as characteristic of biofacies units not implied to be coextensive with these units or the only taxa that form holostratigraphical events within these units. Excludes high Campanian and Lower Maastrichtian chalks that occur in East Anglia. Not to scale. P. Marls, Plenus Marls; M. Rock, Melbourn Rock; C. Rock, Chalk Rock; * the type horizon of *Inoceramus lamarcki* is within the *Inoceramus cuvieri* Biofacies, but it is not the dominant inoceramid at this horizon.

(Norway), and Surlyk et al. (2013) presented a holostratigraphical scheme for the Upper Campanian – Maastrichtian Chalk of eastern Denmark.

Holostratigraphy is particularly useful approach in the Chalk Group where the aim is to use biota to make predictions about lithostratigraphy; the dominance of benthonic macrofossil taxa (for example, brachiopods, bivalves, echinoids and crinoids) means that faunal distributions are more likely to be connected to primary variations of the host sediment. Holostratigraphy provides a framework of stratigraphical data against which to compare fossil occurrences and relative abundances, and allows a more robust and wide-ranging critical assessment of the extent to which components of the biota are likely to be consistently associated with particular formational units. Patterns of broad-scale variability in lithofacies (e.g. flint and marl distribution), combined with a framework of named marker-beds (prominent flint units, marls, sponge beds, hardgrounds) that are a component of Chalk formations, are critical for assessing lateral variability in the ranges of macrofossils, and for providing confidence in biofacies – lithofacies relationships. Following on from this, whole formations, or parts of formations, can be more easily characterised by associations of faunas or relative abundance patterns of faunas that are not otherwise formally recognised as biostratigraphical units, and which may comprise parts of different biostratigraphical

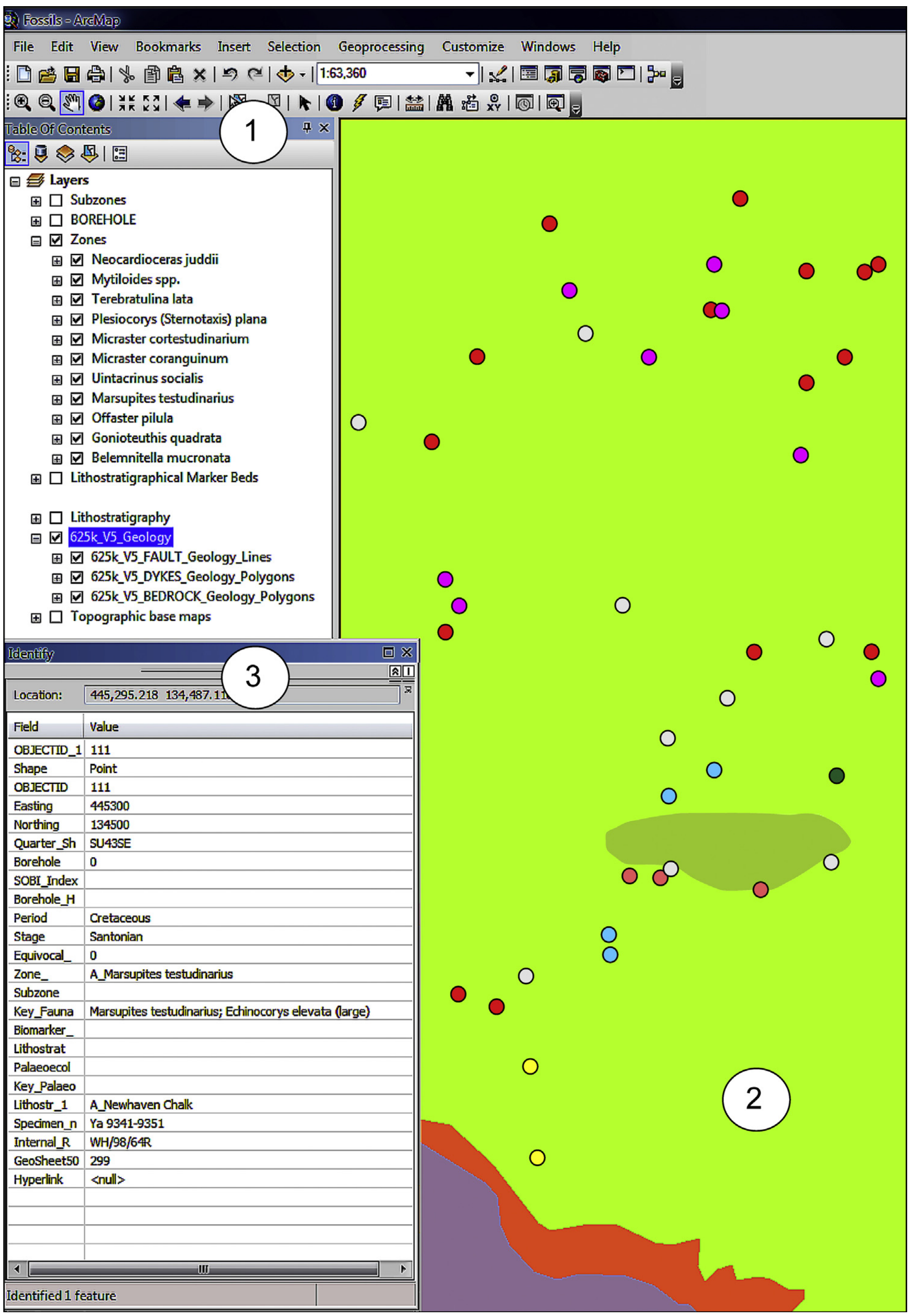

Fig. 3. Display of palaeontological data in a Geographical Information Sysytem (GIS). 1: theme window, showing list of information types that can be selected for display in the map window (for example, digital map data, satellite and aerial photograph data, locality data, biozonal data); 2: map window, showing data layers (in this case geological map and biozonal data, with different coloured dots representing different biozones); 3: information window, showing detailed data for individual layers and points.

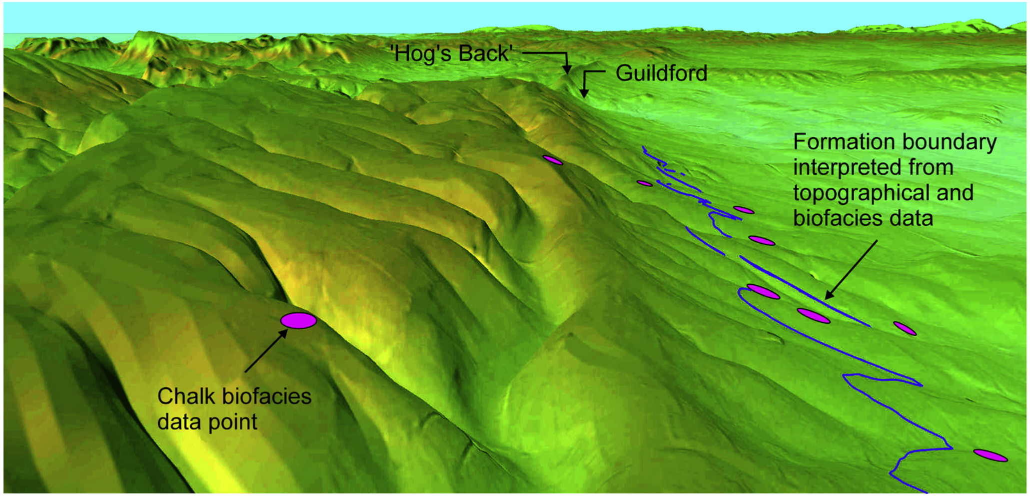

Fig. 4. Use of Geovisionary™ software to display topographical and geological data for part of the North Downs. View looking westwards from Leatherhead towards Guildford and the narrow ridge of steeply dipping Chalk that forms the 'Hog's Back'. In this view, all Chalk biofacies data points are represented by the same colour-code. Some of these biofacies data points, representing a narrow range of stratigraphy, coincide closely with distinct topographical changes, and permit formation boundaries (blue line) to be inferred. These interpretations can be tested through field survey. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

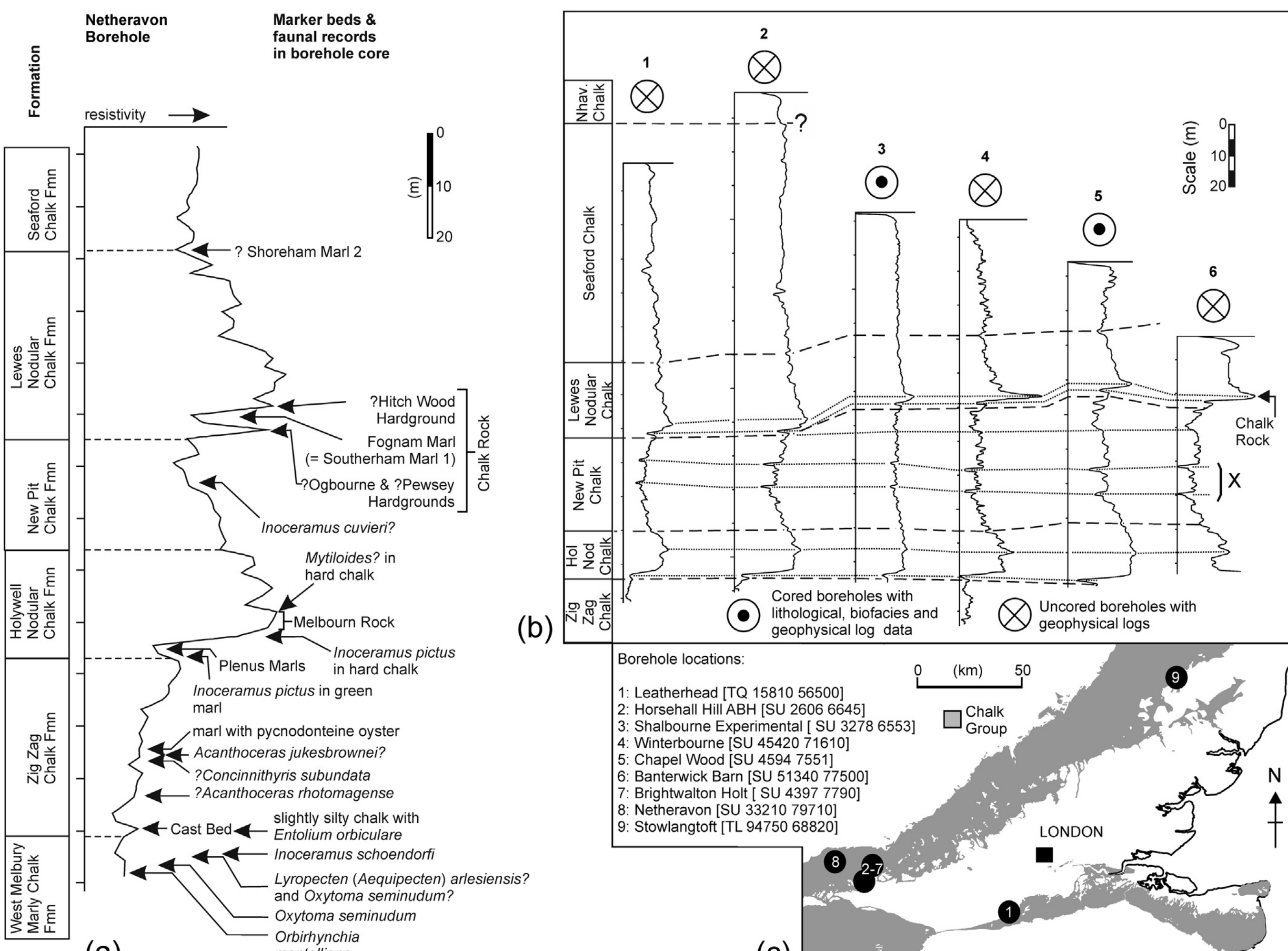

Fig. 5. Using biofacies and lithological data to characterise geophysical logs. (a) relationship of key fossil taxa and marker-beds to the geophysical log in the cored Netheravon Borehole; (b) extrapolating stratigraphical interpretations using geophysical logs from cored boreholes into uncored successions (NB: the thin New Pit Chalk in the Netheravon Borehole, and poor log quality, makes identification of inflection feature 'X' problematic in 5a); (c) location of key cored and geophysically logged boreholes mentioned in the text and figures. See Woods and Aldiss (2004, fig. 5) for explanation of log correlations shown in Fig. 5b.

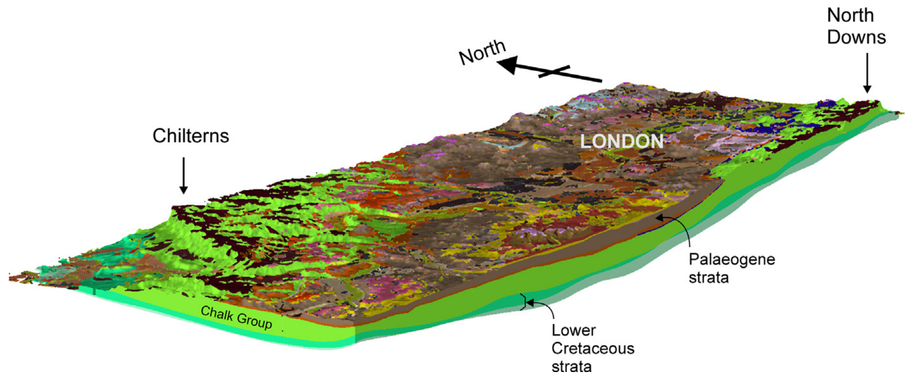

Fig. 6. Image of the BGS London Basin LithoFrame 50 Model, showing three-dimensional perspective view of bedrock and superficial deposits (Burke et al., 2014).

schemes. By considering fossil information in the context of other types of stratigraphical data (for example, contrasting lithofacies features), repeated patterns of particular biofacies, long-ranging biofacies, or incomplete fossil data might usefully be interpreted. In recent decades there has been great progress in understanding the taxonomy of macrofossil groups less widely used in the past for biostratigraphical work in the Chalk, including biozonal schemes for belemnites and inoceramid bivalves, and abundance data for longer-ranging or sporadically occurring faunal groups, such as oysters, bryozoans and certain types of trace fossils (particularly *Zoophycos*). Once amalgamated into a holostratigraphy scheme, these data become collectively more valuable. Fig. 2 shows an informal biofacies scheme that in the course of the BGS work has generally proved useful for predicting lithostratigraphical subdivisions in the Chalk Group. This scheme is not definitive, and the biofacies associations shown in Fig. 2 should be viewed as an iteration of holostratigraphy events derived from macrofossil data for the Chalk Group; other iterations, based on different combinations of fauna, are valid as additional holostratigraphy events.

3. Calibrating landscape features for mapping

The foundations of modern Chalk Group stratigraphy are built on detailed study of coastal cliffs, large inland (quarry) sections, and cored boreholes, where variations in physical characteristics

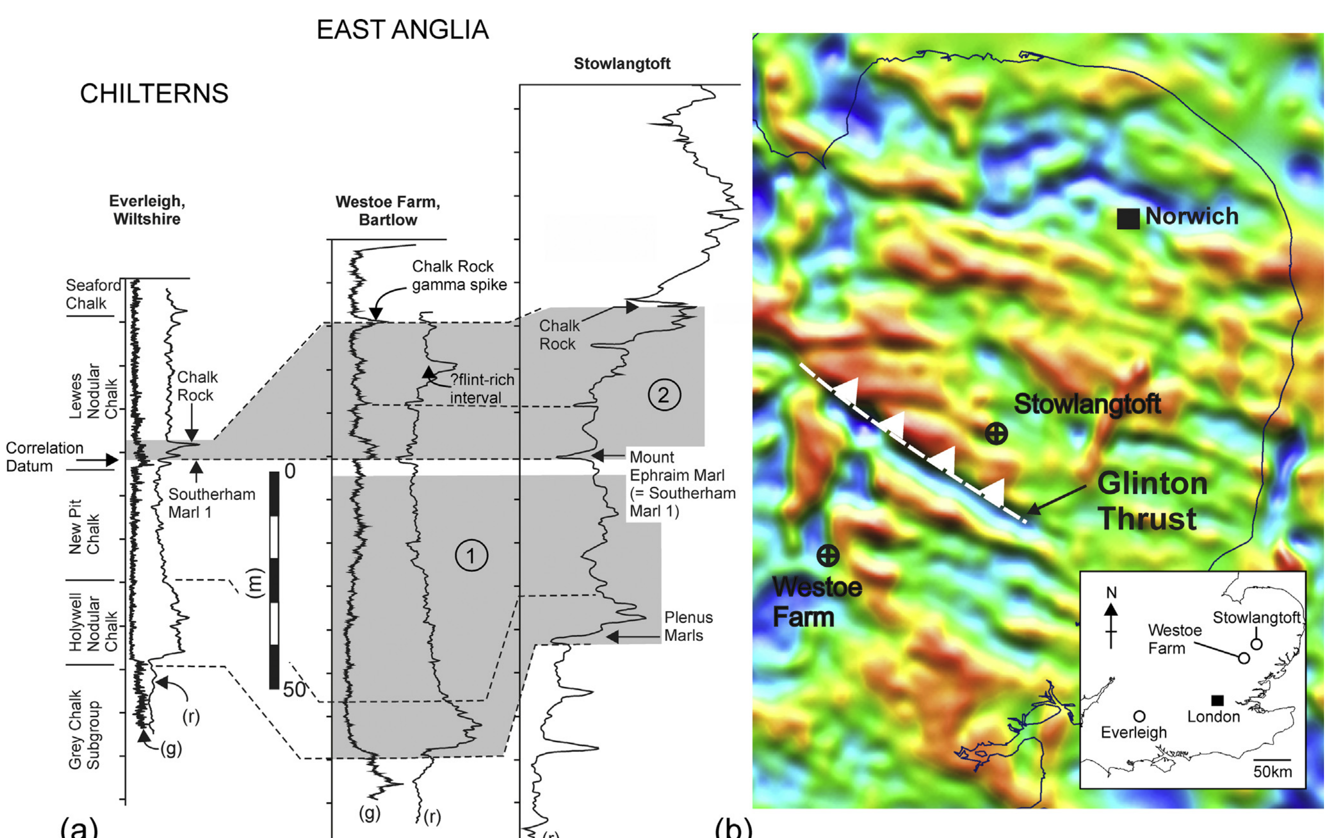

Fig. 7. Combining lithological, biofacies, geophysical log and gravity data to understand patterns of sedimentation in the Chalk Group of East Anglia. (a) Correlation of geophysical logs showing influence of the Glinton Thrust on the thickness of the succession in East Anglia below the Mount Ephraim Marl (1) and above it (2); (b) Regional gravity data for East Anglia showing the linear feature produced by the Glinton Thrust and borehole locations. Log values increase from left to right; g, gamma log; r, resistivity log. See Woods and Chacksfield (2012) for detailed explanation of basis for geophysical log correlation.

and fossil content are easily observed (Mortimore, 1986; Robinson, 1986; Jarvis and Woodroof, 1984; Mortimore et al., 2001). Mapping this stratigraphy across broad, poorly exposed, inland areas is less straightforward, and requires a subtle appreciation of the relationship of landscape features to the underlying bedrock. The methodology used by the BGS has been described by Bristow et al. (1997) and Aldiss et al. (2012), who demonstrated that characteristic breaks of slope coincide with the boundaries of Chalk Group formations. The robustness of this technique relies on ground-truth data where exposure allows, so that the geological interpretations of geomorphological features can be checked against geological reality. The most important sources of ground-truth data in geological surveying are: observations of chalk bedrock in soil ('brash'); locations where chalk is being actively excavated or where outcrop survives in old chalk pits, and archived collections of material from chalk exposures. It is in this last area that palaeontology, viewed in the context of a broader Chalk Group holostratigraphy and coupled with modern computing technology, continues to make a valuable contribution to our understanding of the Chalk. The BGS palaeontology collection, comprising more than 3 million specimens amassed over the last 180 years of survey work, contains a vast amount of material from the Chalk, providing data with the potential for refined stratigraphical interpretation at hundreds of sites, including areas where current outcrop data are sparse. Efficient exploitation of this archive has been optimised in recent years by the development of Geographical Information Systems (GIS), 3D visualisation technology, and the adoption of computer-based survey methods by the BGS. Holostratigraphy criteria are used to interpret the macrofossil archive, considering both the broad biofacies, the significance of any individual faunal elements that may be stratigraphically restricted, lithological data from matrix sediment, and information from nearby outcrops and boreholes. The conclusions for each locality are compiled into databases, with accurate National Grid Reference (NGR) assignment of localities based on cross-matching locality information in BGS Fossil Registers with a digital archive of historical Ordnance Survey maps. These data can be represented as themes within a GIS (Fig. 3), and displayed as points on modern digital base maps with links to the primary data and stratigraphical inferences. Using Geovisionary™ software, the positions of macrofossil data points can be plotted in the context of a 3D visualisation of the landscape features, allowing pre-survey assessment of their potential geological significance (Fig. 4). In the field, the data can be digitally imported onto the base map used by the survey geologist, and considered in the context of other data to understand and geologically calibrate Chalk landscapes.

4. Calibrating the subsurface for modelling

In recent years, the need for better understanding of subsurface Chalk geology has arisen because of the Chalk's important role in water supply, vulnerability to pollution, susceptibility to ground water flooding, and extensive excavation and tunnelling in major

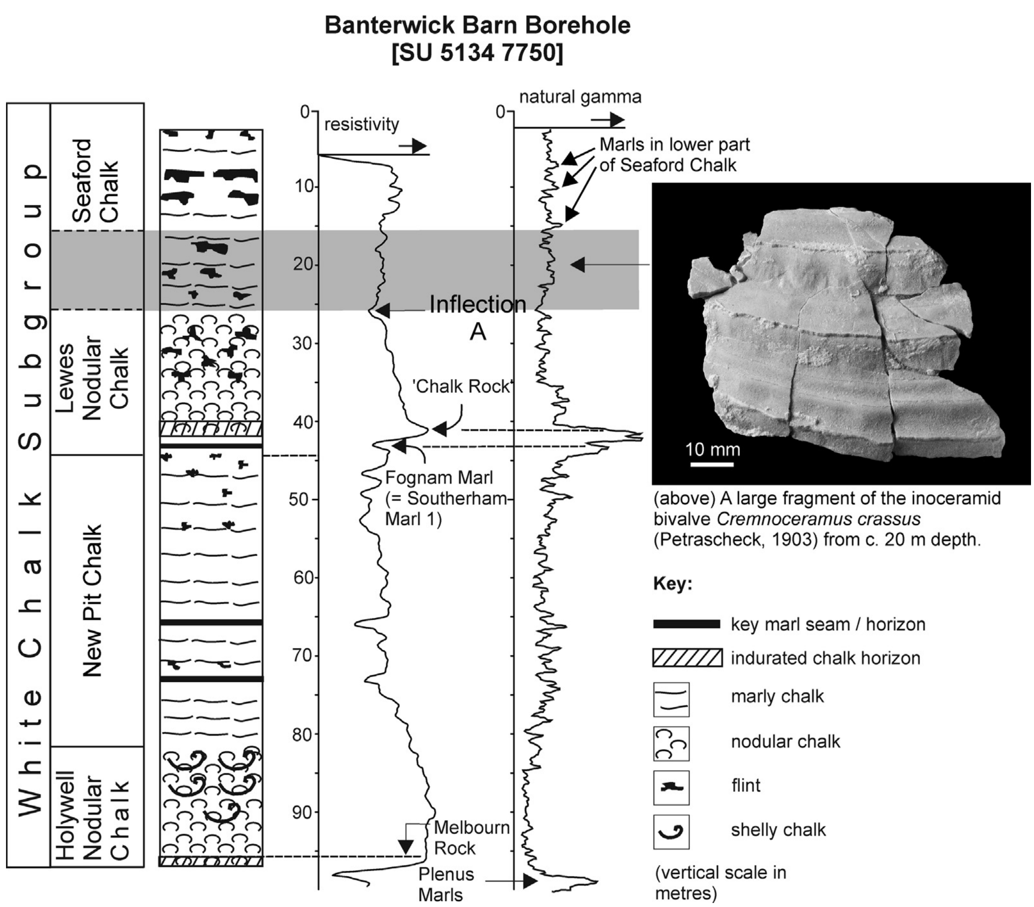

Fig. 8. The Chalk in the Banterwick Barn Borehole in the Berkshire Downs, where fossil data show that strata coeval with the upper Lewes Nodular Chalk (grey shading) have an unusual, poorly cemented texture, possibly showing that deposition at this site (across an inferred shallow marine shelf) was influenced by high productivity of coccolithophores. Inflection A in the trend of the resistivity log marks the boundary between nodular, well-cemented chalk (below) and non-nodular, poorly cemented chalk (above). The top of the grey-shaded interval represents a level equivalent to the base of the stratotype Seaford Chalk in Sussex. See Woods and Aldiss (2004) for more detailed discussion of the relationship between lithofacies, biofacies and geophysics.

civil engineering projects. Many written descriptions of boreholes are too poor to allow accurate interpretation of modern Chalk lithostratigraphy, but extensive archives of borehole geophysical logs can be used (Mortimore, 1986; Mortimore and Pomerol, 1987; Woods, 2006) provided that the signatures can be confidently interpreted. For this to be achieved, cored boreholes are required so that the lithology and biofacies that are used to recognise Chalk formations in core can be depth-matched to geophysical logs for these boreholes. Good examples are the Netheravon, North Farm, Winterbourne and Banterwick Barn boreholes in the Berkshire Downs, Leatherhead Borehole in Surrey, and Stowlangtoft Borehole in Suffolk (Fig. 5). Biofacies data has been particularly helpful in geophysically characterising the junction between the West Melbury Marly Chalk and Zig Zag Chalk formations, a boundary interval associated with distinctive lithological units characterised by particular fossil associations (Woods and Aldiss, 2004). These boreholes provide a network of control points from which correlations can be made using boreholes for which geophysical logs provide the only stratigraphical data. The results of this work show that there are regular patterns to certain types of geophysical logs (especially electrical resistivity logs) that are widely repeated across southern England, which can be confidently related to the formational stratigraphy mapped by the BGS. Correlations based on geophysical log inflections form a fundamental component of 3D models of the Chalk (Fig. 6), linking landform profile information with surface geological data from mapping and subsurface geological interpretations from boreholes and seismic data.

5. Revealing new understanding of the Chalk Group

At a detailed level, palaeontological data has challenged our understanding of the Chalk, and forced us to think more deeply about the environmental processes influencing its deposition. Understanding the nature of these processes, and how they may have varied across the depositional basin with respect to postulated water depth or geological structure, has an important role in predicting patterns of regional variation in the Chalk where this might not otherwise be easily observed. Below are selected examples of how palaeontology has provided insights into our understanding of patterns of Late Cretaceous sedimentation and the factors that influenced it.

5.1. The Chalk of East Anglia

In East Anglia, work by Mortimore and Wood (1986) showed how the abundances of certain fossils could be used to identify marl seams (thin, mud-rich chalk units) with their named equivalents in southern England. Woods and Chacksfield (2012) used these results, combined with data from the cored Stowlangtoft Borehole, to trace these marl seams on geophysical logs

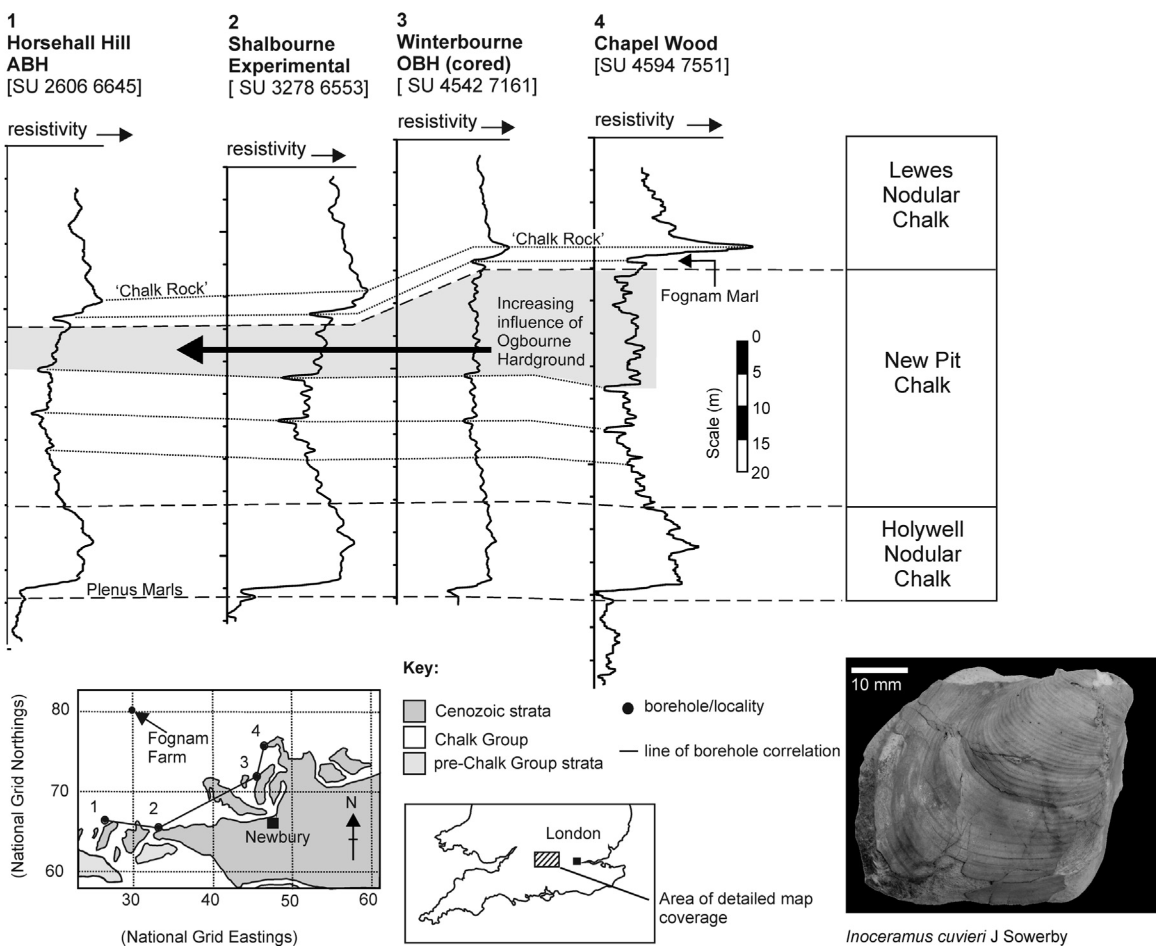

Fig. 9. Lateral variation in the extent of erosion/winnowing associated with the lowermost hardground (Ogbourne Hardground) of the Chalk Rock in the Berkshire Downs. The grey-shaded area is inferred to be within the *Inoceramus cuvieri* Biofacies based on the record of this facies further north/west below the strongly developed Ogbourne Hardground at Fognam Farm, and based on geophysical log correlation with the cored Banterwick Barn Borehole further east, where the Ogbourne Hardground is absent. This shows that strata coeval with the higher part of the New Pit Chalk in Sussex are variably affected by erosion/winnowing associated with the Ogbourne Hardground, but are unlikely to have been completely removed. See Woods and Aldiss (2004) for detail of geophysical log correlations.

across East Anglia. The correlation revealed the likely influence of deep basement faults on the depositional development of the Chalk; faults that are imaged on regional gravity data and that originally formed during the early Palaeozoic history of East Anglia (Fig. 7). The work also identified the development of a thick (c. 30 m) interval of poorly cemented chalk, corresponding with much thinner, highly cemented successions across Southern England. It seems that whilst much of Southern England experienced erosional winnowing of chalk associated with variable patterns of sea level fall and transgression (Gale, 1996), marine circulation across East Anglia may have favoured unusually high productivity of chalk. This work serves as a reminder that Chalk itself is a biogenic deposit, composed of the skeletons of countless billions of calcareous planktonic algae (coccolithophores), and that the distribution of the Chalk is not just a response to available accommodation space within the depositional basin, but also to the ecological factors that affected the near surface waters that these photosynthesising plankton inhabited.

5.2. The Berkshire Downs

In the Berkshire Downs, fossil (particularly the inoceramid bivalve *Cremnoceramus crassus* (Petrascheck, 1903)), lithological and geophysical data from the Banterwick Barn Borehole shows that strata equivalent to the Lewes Nodular Chalk are unusually thick and poorly cemented across parts of the Chilterns (Fig. 8);

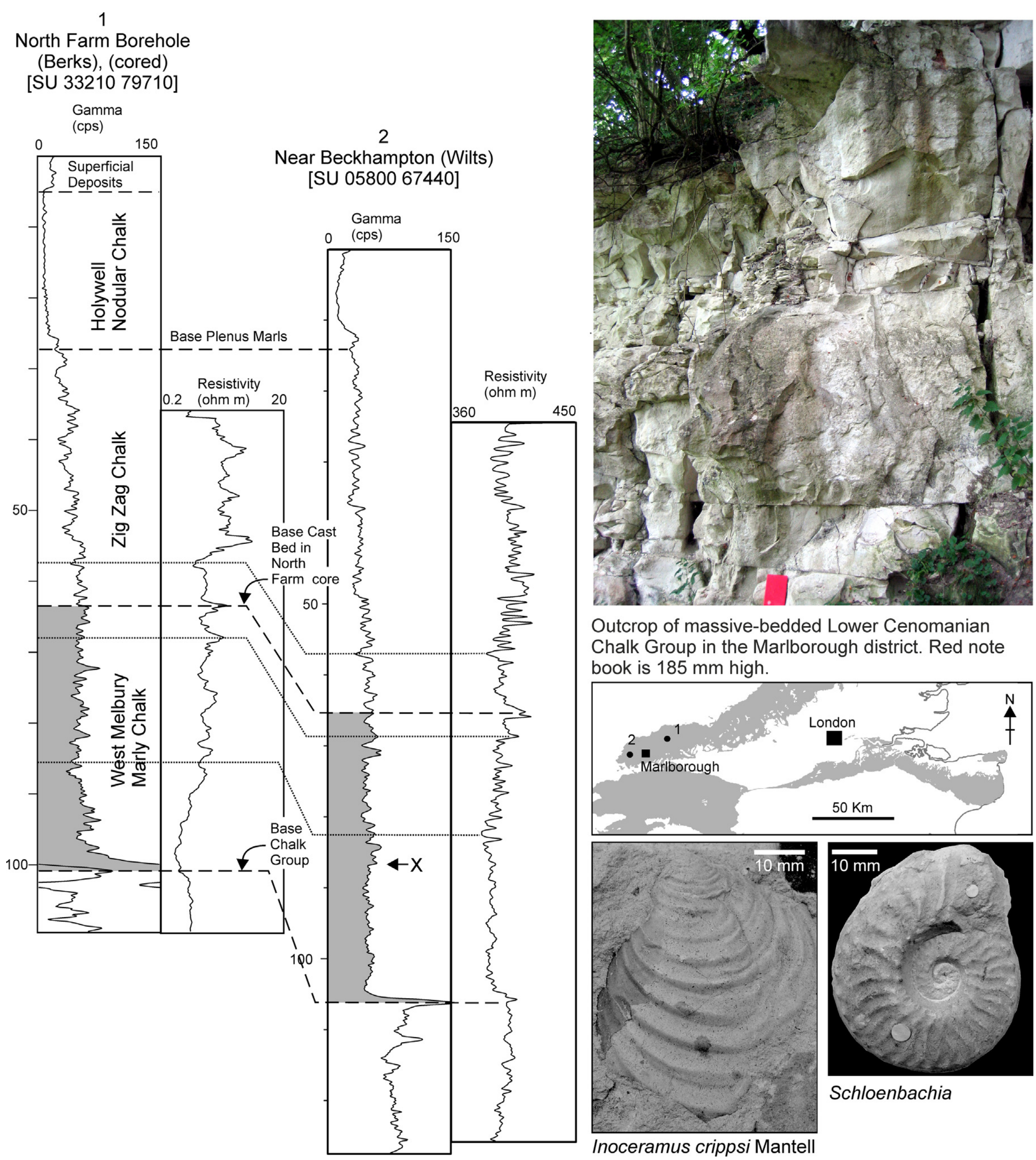

Fig. 10. Unusual development of massive-bedded, poorly rhythmic lower West Melbury Marly Chalk in the Marlborough district, with well-developed *Inoceramus crippsi* - *Schloenbachia* Biofacies. The geophysical logs show that the Grey Chalk Subgroup (= combined West Melbury Marly Chalk & Zig Zag Chalk) is very thick (+90 m), with the lowest 20 m of Chalk in the Beckhampton log (below 'x') displaying a lower amplitude, less serrated gamma signature, consistent with outcrop evidence for weakly developed sediment rhythmicity. There are also strong contrasts in the resistivity logs of the higher parts of the Beckhampton and North Farm boreholes. This may be evidence for the onset of (anomalous) strongly rhythmic sedimentation in the higher part of the Beckhampton Grey Chalk succession, although this is speculative.

thicknesses are comparable to the stratotype in Sussex where this part of the succession is more strongly nodular in texture (Woods and Aldiss, 2004). This conclusion is perplexing, because the Berkshire Downs – Chilterns region has widely been interpreted as a relatively shallower part of the depositional basin across which hardgrounds (Chalk Rock, Top Rock) developed in the lower part of the Lewes Nodular Chalk (Late Turonian and earliest Coniacian). Either a radical change of basin architecture is indicated, or, like East Anglia, it may reflect ecological conditions that favoured coccolithophore productivity. Unusual environmental conditions are also hinted at in historical accounts of the Chalk of this region, which refer to macrofossils being especially sparse in the biozonal equivalent (*Micraster cortestudinarium* Zone) of the upper Lewes Nodular Chalk, and the succession closely resembling that which typifies the younger *Micraster coranguinum* Zone (White, 1907).

5.3. Thickness variation of the New Pit Chalk Formation

Across southern England, Gale (1996) showed that the New Pit Chalk displays pronounced lateral changes in thickness, largely due to variable erosion at the base of a hardground (Ogbourne Hardground), which in some areas approximately marks the base of the overlying Lewes Nodular Chalk Formation. The Ogbourne Hardground varies in its geographical development; as it fades eastwards Gale (1996, fig. 5) showed that the New Pit Chalk thickens into Sussex, and this is demonstrated by resistivity log correlations in the Berkshire Downs (Fig. 9). The higher part of the New Pit Chalk typically contains an inoceramid biofacies dominated by *Inoceramus cuvieri* J Sowerby, 1814, which continues upwards into the lower part of the overlying Lewes Nodular Chalk. There has been some debate about the extent of erosion associated with the formation of the Ogbourne Hardground, which may be very extensive (Gale, 1996), and remove sediment that typically preserves the *I.cuvieri* Biofacies. However, the record of this biofacies below the Ogbourne Hardground at Fognam Farm [SU 296 800], in Berkshire (Woods and Aldiss, 2004), suggests that the pattern of erosion is more variable and may be responding to local patterns of structurally controlled basin architecture. In northern East Anglia, the *I. cuvieri* Biofacies seen in a borehole near Bircham, Norfolk, sits directly on top of the shell-rich *Mytiloides* Biofacies I characterising the Holywell Nodular Chalk, and points to elimination of strata equivalent to the lower part of the New Pit Chalk, a conclusion supported by structurally-induced thinning of the lower New Pit Chalk in central East Anglia (Woods and Chacksfield, 2012; Fig. 7).

5.4. The Marlborough Downs

Finally, at the edge of the Marlborough Downs, the Grey Chalk Subgroup shows unusual patterns of facies in its lower part. The typically strong marl/limestone rhythmicity that has been widely described across the UK and Europe (Gale, 1995) is much less clear (Fig. 10). Although in appearance the succession seems more typical of the Upper Cenomanian, the macrofossil fauna unequivocally belongs to the *Inoceramus crippsi – Schloenbachia* Biofacies of Fig. 2, proving the strata equate with the Lower Cenomanian West Melbury Marly Chalk Formation. Geophysical logs from the North Farm Borehole in the Berkshire Downs, where the junction of the West Melbury Marly Chalk and Zig Zag Chalk was geophysically characterised (Woods and Aldiss, 2004), can be matched with geophysical logs in the Marlborough Downs, showing an unusually thick (+90 m, compared to c. 70 m at North Farm) Grey Chalk Subgroup (Fig. 10). Gamma logs from the succession (Fig. 10) suggest that the marl rhythms in the lower part of the succession might have been diluted by high coccolithophore productivity, perhaps across a zone showing a relatively rapid change in basin bathymetry. Archive borehole records for the Marlborough Downs describe thick 'Lower Chalk', and historical annotations to these logs state that this must be a mistake – not so say the fossils!

In many of the examples given above, a conventional biostratigraphical approach to the Chalk, identifying named zones and subzones, would not have been sufficiently nuanced to reveal any lateral contrasts in sedimentary development. Historical biostratigraphical work on the equivalent of the New Pit Chalk would have relied on accurate identification of a few key fossils to identify the *T. lata* Zone, an interval that spans the whole formation and in many places also extends into the lower part of the overlying Lewes Nodular Chalk.

6. Conclusion

Palaeontology became important in the historical development of Chalk stratigraphy because of an over-simplified lithological subdivision that offered limited scope for description of its relative age and distribution. Despite this, historical use of Chalk palaeontological data was rather simplistic relying on a relatively small number of key taxa to identify units that are in some cases quite broad. The development of a more refined lithostratigraphical scheme, with a detailed marker-bed framework, has allowed a rigorous assessment of the stratigraphical distribution of a large number of different fossil groups in the Chalk, and identification of biofacies units. As a component of a Chalk holostratigraphy framework, these biofacies provide valuable supporting data for Chalk mapping, and allow characterisation of subsurface Chalk formations expressed in borehole geophysical logs used to build 3D geological models. Palaeontological data from outcrops and boreholes can be used to understand lateral changes in the geometry of discrete packages of chalk sediment, showing that in some areas deposition was influenced by long-lived basement structures, or patterns of ocean circulation and fertility affecting the near-surface waters inhabited by chalk-forming phytoplankton.

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