The Chalk of Suffolk

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From its broad expanses of rolling downlands across southern England, the Late Cretaceous Chalk Group sweeps northwards across much of East Anglia, and on into Lincolnshire and Yorkshire. The Chalk is the major bedrock unit across Suffolk, and dips gently eastwards beneath much of the East Anglia region. The oldest strata are locally exposed along the western margin of the outcrop, for example near Mildenhall, and progressively younger horizons are introduced eastwards towards the coast. Consequently, the Chalk is thickest in the eastern part of the Suffolk region, reaching about 250 m in the Combs Borehole [TM 0427 5625] near Stowmarket; perhaps close to 300 m beneath Ipswich; and about 321 m in a borehole at Lowestoft [TM 5380 9260] (Moorlock *et al*., 2000). Northwards, boreholes in Norfolk have proved more than 400 m of Chalk at Trunch [TG 2933 3455] (468 m); Somerton [TG 4607 2120] (433 m); and West Somerton [TG 4736 1935] (423 m) (Arthurton *et al*., 1994), at least part of this increased thickness being attributable to the preservation of younger chalk in the upper parts of these successions. Just as in neighbouring Essex and Norfolk, much of the Suffolk Chalk is buried beneath a variable succession of post-Cretaceous, predominantly Quaternary deposits, but including Palaeogene and Neogene strata in the south-east of the county. For this reason, the region has not developed the typical downland landscape of southern England, and our geological understanding of the Chalk of Suffolk has to be assembled from rare natural exposures, chalk quarries and borehole data.

The general tectonic and basin setting of the Chalk of Suffolk, and the wider East Anglia region, is unusual in that Lower Palaeozoic and older Neoproterozoic rocks are at shallow depths. For much of the Late Palaeozoic and Mesozoic the area was occupied by the Anglo-Brabant Massif, which formed a persistent land area or region of shallow marine deposition, including the area referred to as the 'London Platform' (Fig. 1). It was not until the Albian, when the mudstones of the Gault were deposited, that this persistent palaeogeographical feature became completely submerged.

Today, the main areas in Suffolk where Chalk crops out are in the north-west of the county around Bury St Edmunds, Brandon, Icklingham and Barnham. Southwards and eastwards there are significant exposures of Chalk at Sudbury and in the Gipping Valley, for example at Needham Market and Great Blakenham; there are also minor, isolated occurrences in the vicinity of Haverhill, Nedging Mill and Monks Eleigh (Fig. 2). Information about the subsurface development of the Chalk in Suffolk is provided by cored stratigraphical boreholes, such as the Stowlangtoft Borehole [TL 9475 6882]; boreholes drilled in connection with the Ely-Ouse Transfer Scheme; site investigation boreholes near Mundford and in the Ipswich area, the former (CERN Project) for a large proton accelerator, and the latter (Project Orwell) as part of a flood relief scheme; cored site investigation boreholes drilled at Sizewell; and a cored borehole at Clare, near Sudbury (Fig. 1). There are also numerous borehole geophysical logs from uncored boreholes and water wells, particularly in the north of the county.

Fig. 1. Key tectonic structures affecting sedimentation of the Chalk in East Anglia, particularly Suffolk. Glinton Thrust and Basement Lineament are derived from the gravity anomaly map Fig. 9. The Midlands Microcraton margin and the Lilley Bottom Structure are derived from the BGS 1:500 000 Series Tectonic Map of Britain, Ireland, and adjacent areas (Pharaoh *et al*., 1996). SB = Sudbury–Bildeston Ridge; B St Ed = Bury St Edmunds; L = Lavenham; K = Kersey; 1, 2, 3, 4, 5, 6, boreholes shown on Fig. 2
WF = Whitham Fault; WBF = Wickham Bishops Fault; GF = Galleywood Fault; CF = Cliffe Fault; PA = Purfleet Anticline; GA = Greenwich Anticline; GF = Greenwich Fault; SF = Streatham Fault; Wim F = Wimbledon Fault.

In areas such as East Anglia, and particularly Suffolk, where the Chalk is poorly exposed, there are inherent problems in understanding how the widely scattered outcrops relate to each other. In Suffolk, the extensive post-Cretaceous cover and consequent paucity of geomorphological data, gives added weight to the need to understand the physical character of the Chalk and the development of distinctive lithological horizons ('marker-beds'), for example distinctive flint bands, marl seams and hardgrounds. Many have been formally named and, because each is believed to represent a broadly synchronous event, they form an important framework for correlation. Additionally, some of the marl seams have been shown to be volcanogenic in origin, and represent near-isochronous events across north-west Europe

(Wray & Wood, 1995, 1998; Mortimore *et al*., 2001, fig. 1.12). The marker-bed scheme applied in East Anglia is primarily based on marl seams, and is partly based on local schemes derived from the CERN Project (Ward *et al*., 1968), as well as extrapolating from the most applicable established named marls in adjacent regions (Fig. 3). In the subsurface this framework of detrital and volcanogenic marls is well displayed as pronounced inflections on borehole resistivity logs.

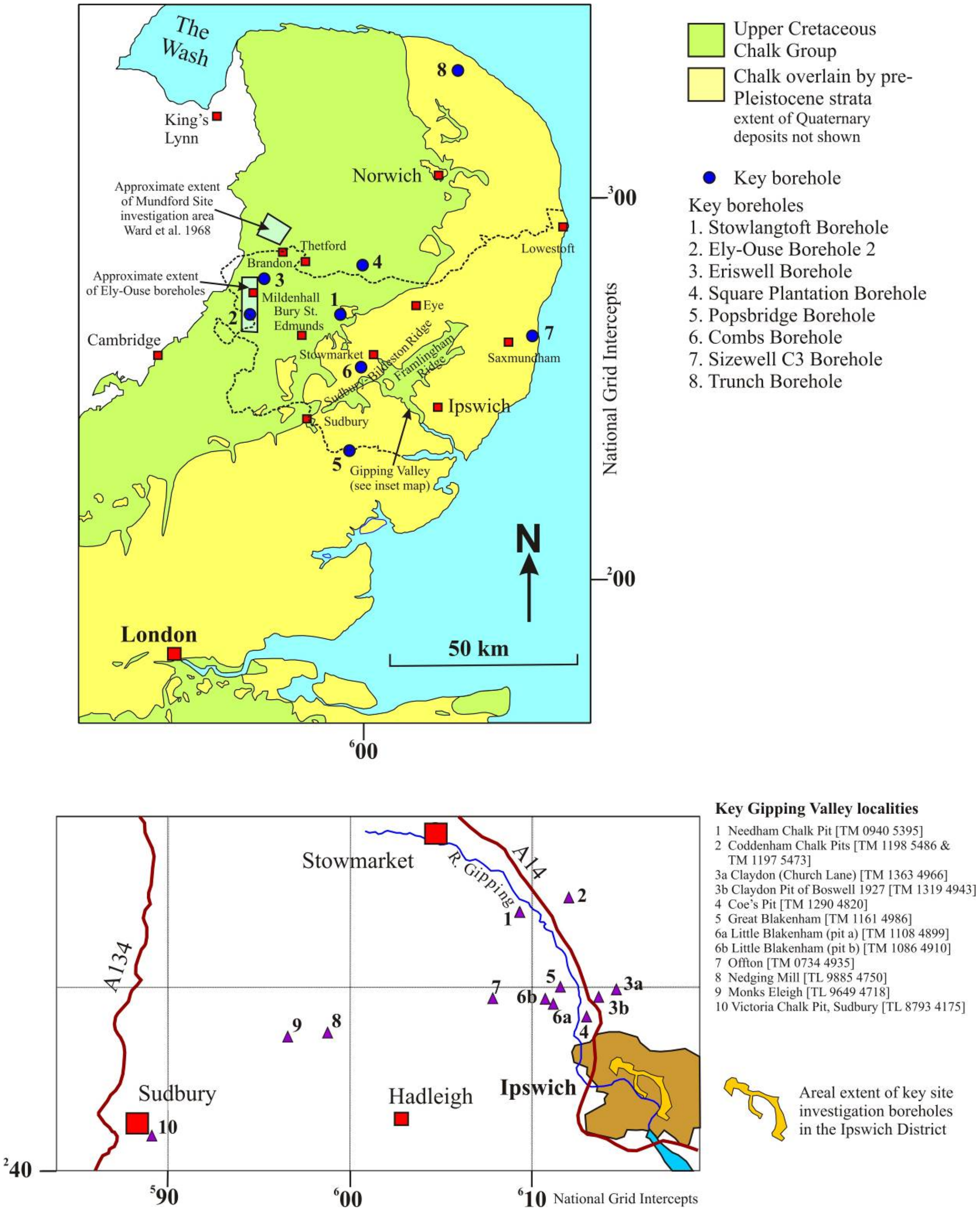

Fig. 2. Localities and boreholes referred to in the text. Partly based on Woods *et al*. (2007).

Previous research

In *The Cretaceous Rocks of Britain*, Jukes-Browne & Hill (1903, 1904) gave the first general description of the Lower, Middle and Upper Chalk of Suffolk, as it was then known. Their main focus was the area of Chalk crop in the north-west of the county, around Bury St Edmunds, but they also detailed the Upper Chalk near Sudbury and in the Gipping Valley, near Ipswich. A more detailed, and geographically comprehensive treatment of the biozonal development of the Upper Chalk in Suffolk was provided by Jukes-Browne (1904), and in the following years of the early 20th century there was a flurry of research on the Chalk of Suffolk, particularly centred on the character and age of the Chalk in the Gipping Valley (Boswell, 1912, 1913, 1927; Brydone, 1932). At the same time, Hewitt (1924, 1935) made a systematic biozonal study of chalk pits in and around Thetford, which included the Chalk crop in northern Suffolk around Lakenheath, Mildenhall and eastwards towards Honington. Few of these chalk pits still survive, and Hewitt's work provides an invaluable record of the age and character of the Chalk seen in the north-west of the county. More recent work on the Chalk of Suffolk dates mainly from the 1980s onwards, beginning with work by Murray (1986) on the correlation of borehole geophysical logs. Stratigraphical control for these correlations, extending from southern England across East Anglia and into Lincolnshire and Yorkshire, in part relied on earlier work by Ward *et al*. (1968), which investigated the detailed subsurface stratigraphy of the Chalk at Mundford, a few kilometres north of Brandon. Mortimore & Wood (1986) also investigated the successions around Brandon as part of a broader study of flint distribution in the Chalk, and crucially recognised marker beds that had been newly defined in a revised lithostratigraphical scheme for the Chalk based on successions in southern England (Mortimore, 1986). Concurrently with this work, the British Geological Survey (BGS) began a programme of systematic surveys in East Anglia which have greatly expanded our knowledge of the Chalk of Suffolk, as detailed in the accompanying memoirs and sheet explanations, including Bury St Edmunds (Bristow, 1990), Sudbury (Pattison *et al*., 1993), Ely (Gallois, 1988), Lowestoft and Saxmundham (Moorlock *et al*., 2000), and Ipswich (Mathers *et al*., 2007).

Modern regional and national perspective

Traditionally, the Chalk was subdivided into three broad units: Lower Chalk, Middle Chalk and Upper Chalk, with the boundaries marked by hard beds that formed distinctive features in the landscape; the Melbourn Rock at the junction of the Lower and Middle Chalk, and the Chalk Rock at the Middle/Upper Chalk junction (Fig. 3A). Another hard bed (Totternhoe Stone) was traditionally mapped within the Lower Chalk, the succession below this being designated the Chalk Marl, and the succession above representing the Grey Chalk.

At a meeting of Chalk stratigraphers at the British Geological Survey in 1999 (summarised in Rawson *et al*., 2001) the Chalk was assigned Group status, and subdivided into a lower, generally more mud-rich, Grey Chalk Subgroup, and a much thicker interval of generally pure white Chalk, named the White Chalk Subgroup. These two subgroups broadly correspond to the Lower Chalk and Middle plus Upper Chalk respectively, but differ in that the base of the Plenus Marls rather than that of the overlying Melbourn Rock is taken as the base of the White Chalk Subgroup. Within these subgroups a variable number of formations are recognisable in different areas, depending on the extent of pre-Palaeogene and later Quaternary erosion (Figs. 3A, B).

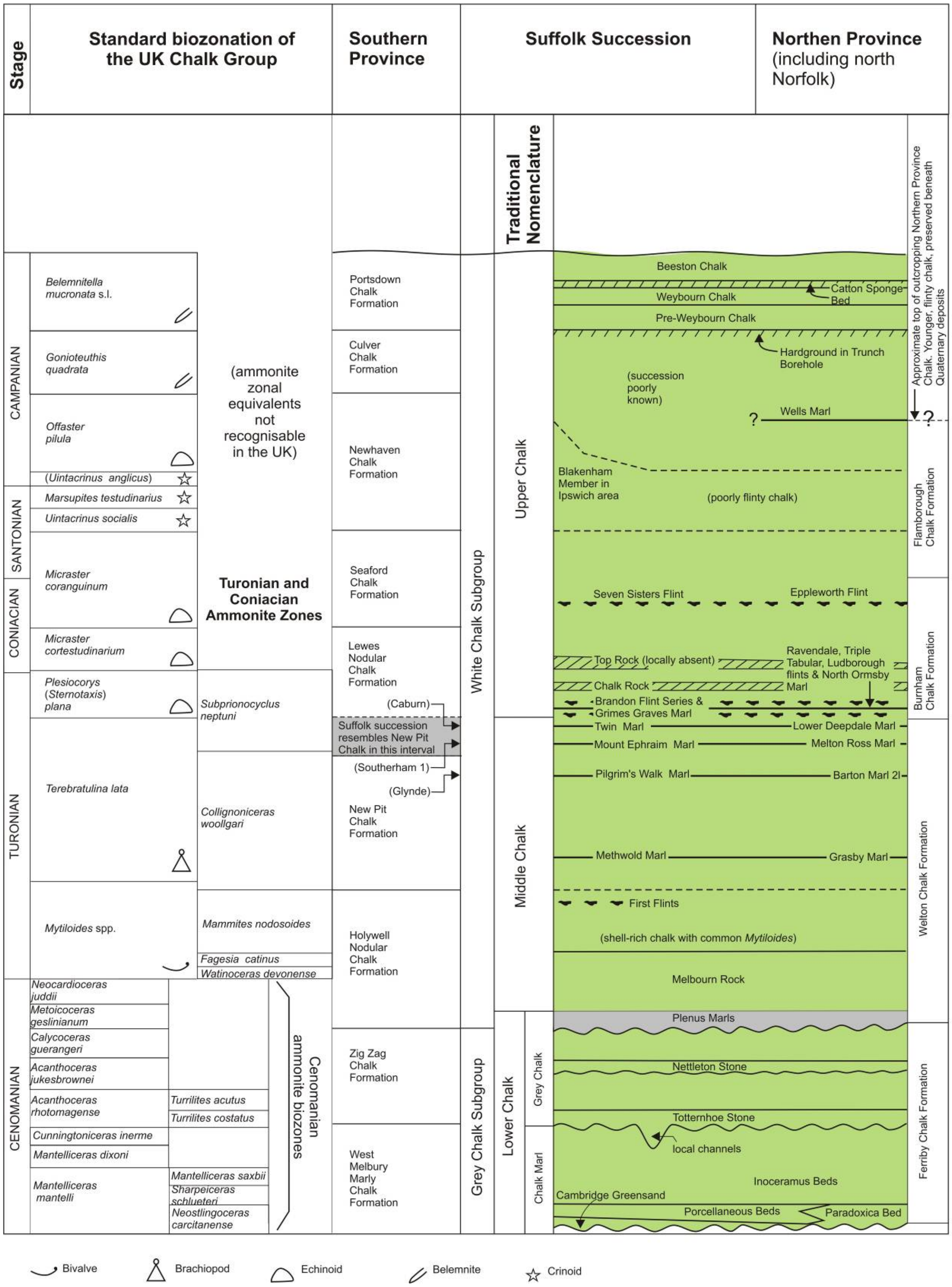

Fig. 3A. The stratigraphy of the Chalk of Suffolk compared to the successions in the Northern and Southern provinces (not to scale). *U. anglicus* Zone not recognised in East Anglia.

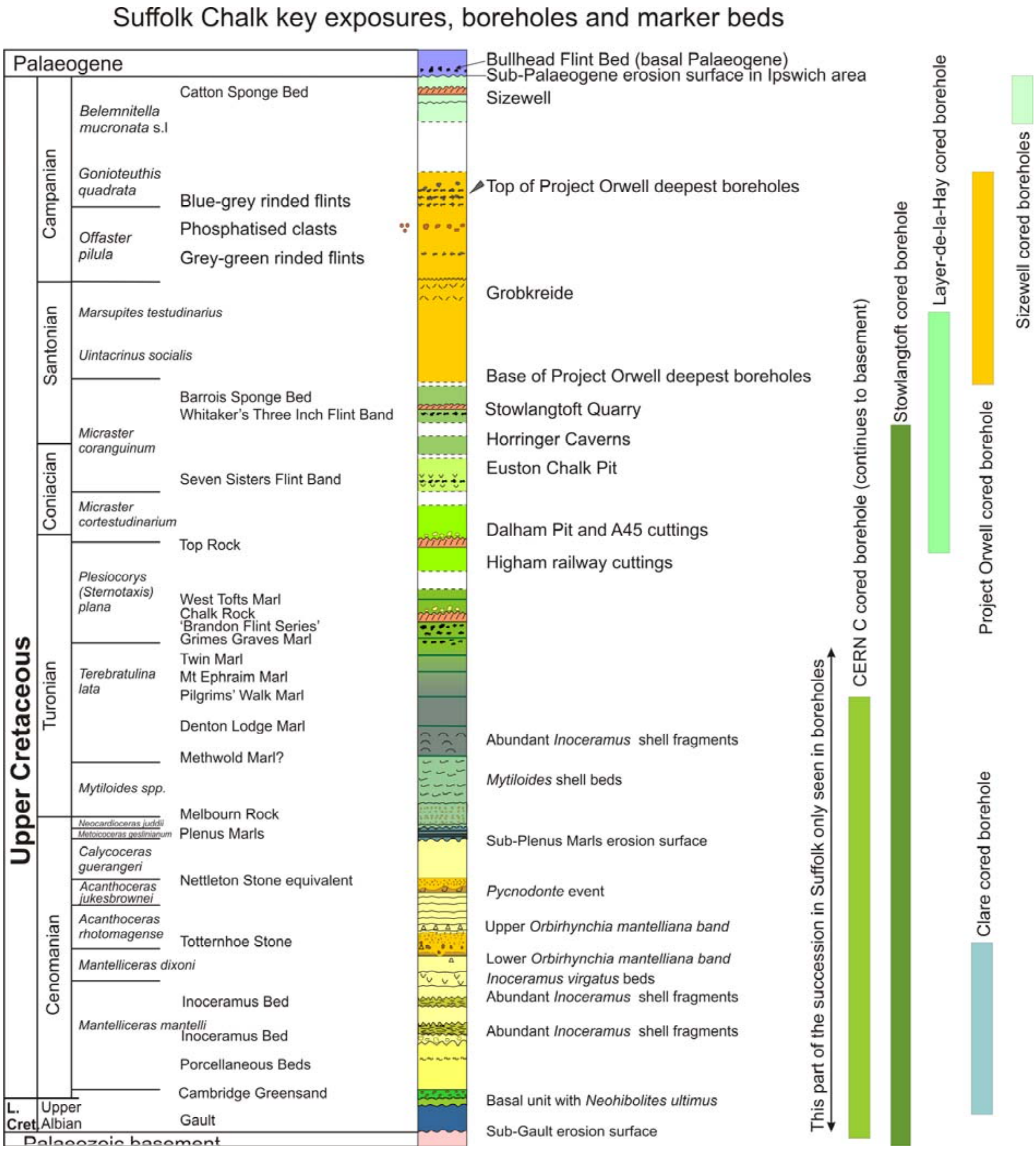

Fig. 3B. Schematic geological section illustrating the main elements of the stratigraphy of the Chalk of Suffolk, the limited and non-continuous exposures (small pits and quarries) and the cored boreholes that help fill the gaps (not to scale).

The renaissance of research into the Chalk that has occurred in the last 20 years has led to new lithostratigraphical schemes for the Chalk of southern and northern England. These schemes are largely based on the work of Wood & Smith (1978), Wood in Gaunt *et al*. (1992) and Whitham (1991, 1993) for northern England; and Mortimore (1986) and Bristow *et al*. (1997) for southern England. It was earlier recognised (Wood & Smith, 1978) that the Chalk of Yorkshire, Lincolnshire and, at some stratigraphical levels in northern Norfolk, belonged to a different faunal and depositional province from the Chalk of southern England. These were designated the Northern and Southern Provinces respectively. However, it was acknowledged that neither the Northern Province nor the Southern Province lithostratigraphical schemes were wholly applicable to East Anglia; in some cases elements of the two schemes appeared to be mixed across the region, and Mortimore (1983) aptly coined the term 'Transitional Province' for the greater part of East Anglia and the adjacent Chilterns region. There is also some evidence for the development of new lithostratigraphical units unrepresented in either of the classifications for northern or southern England, for example in the Gipping Valley (Woods *et al*., 2007).

In the time that has elapsed since 1999, there has been relatively little progress in developing a lithostratigraphical classification that is applicable to East Anglia. Although the Grey Chalk and White Chalk subgroups are recognisable, poor exposure and lack of detailed borehole data prevent a comprehensive understanding of the lateral and vertical variation in the Chalk of East Anglia, including the Suffolk region. For these reasons, this account of the Chalk of Suffolk uses the most appropriate Chalk formations based on comparison of the Suffolk succession with the lithostratigraphical schemes for the Southern and Northern provinces. It is acknowledged that in some cases this is problematic, and is intended to be the subject of a future publication. The relationship of traditional and modern lithostratigraphical and biostratigraphical schemes for the Chalk is shown in Fig. 3A, together with key features of the Suffolk Chalk succession (Fig. 3B).

Grey Chalk Subgroup

Ferriby Chalk Formation

The lower part of the Chalk, between its basal erosional contact and the sub-Plenus erosion surface immediately underlying a clay-rich unit called the Plenus Marls Member, is designated the Grey Chalk Subgroup in both the Southern and Northern Province successions. These erosion surfaces occur across the Suffolk and wider East Anglian region, and Grey Chalk Subgroup can be used for most of the strata formerly classified as Lower Chalk in this region. In Suffolk the subgroup, with the exception of the basal beds, compares more closely with the Ferriby Chalk (*sensu* Hopson, 2005) of the Northern Province rather than the correlative West Melbury Marly Chalk and Zig Zag Chalk formations of the Southern Province. In the Stowlangtoft Borehole, the Ferriby Chalk is about 47 m thick.

The base of the Chalk Group crops out west of Lakenheath, but there are no records of good exposures, either currently or in the historical literature. Data are available from the Ely-Ouse boreholes as well as the cored boreholes at Eriswell [TL 7423 7887], near Mildenhall; Stowlangtoft [TL 9475 6882] near Bury St Edmunds; and Clare [TL 7834 4536], near Sudbury. These show that the base of the Chalk is a very distinctive, thin (typically less than one metre thick), micaceous, clayey bed with abundant brown and black phosphatic concretions and common glauconite grains, named the Cambridge Greensand (Fig. 3; see discussion in Morter & Wood 1983; Wood & Bristow, 1990; Mortimore *et al.*, 2001). Locally, in Ely-Ouse Borehole 6 [TL 69270 73080], the basal part of the Cambridge Greensand is poorly glauconitic and sparsely phosphatic. The Cambridge Greensand contains phosphatised Late Albian fossils derived from the erosion of the top of the underlying Gault, as well as indigenous Early Cenomanian taxa. These fossils include bivalves (especially *Aucellina*), large brachiopods and rare ammonites (Pattison *et al.*, 1993; Wood & Bristow, 1990). The Cambridge Greensand has a relatively limited development across East Anglia; northwards it disappears near Marham in Norfolk (Gallois & Morter, 1982), and south-westwards is appears to be truncated against a fault or monoclinal structure near Leighton Buzzard referred to as the Lilley Bottom Structure (Fig. 1; Hopson *et al.*, 1996).

Above the Cambridge Greensand, the lower part of the Grey Chalk Subgroup in the Suffolk boreholes does not show the typical marl/limestone rhythmicity seen in the area from Cambridge south-westwards to the Lilley Bottom Structure, and more widely across the Southern Province. In Suffolk, the Cambridge Greensand is overlain by an interval of creamy-coloured, smooth-textured, chalky limestones, named the Porcellaneous Beds (Morter & Wood, 1983; Wood & Bristow, 1990; Pattison *et al*., 1993; Fig. 3), which correlate to the north with the Paradoxica Bed of the standard basal Ferriby Chalk succession. The Porcellaneous Beds contain a low diversity fauna largely comprising thin-shelled *Aucellina*, with poorly preserved heteromorph ammonites and inoceramid bivalves towards the top. They are overlain, with marked colour and textural contrast, by two units of grey shell-detrital chalk, the Inoceramus Beds, each with a well-marked basal erosion surface and separated by finer-grained chalk. The lower of these beds contains glauconitised pebbles above the erosion surface and crushed complete specimens and large pieces of the bivalve *Inoceramus crippsi*, indicating the *Sharpeiceras schlueteri* Subzone of the *Mantelliceras mantelli* Zone (see Fig. 3A). These distinctive beds were proved in the Clare Borehole (Pattison *et al*., 1993, fig. 12) and were used as marker horizons in the correlation of the Ely-Ouse boreholes (Gallois, 1988, fig. 26). They are followed further upsection by a unit of much paler-coloured and finer-grained massive chalks with abundant three-dimensional, bivalved *Inoceramus virgatus* indicating the *Mantelliceras dixoni* Zone, which in turn are succeeded by marl/limestone rhythmites.

At least two beds of rather sandy and gritty chalk occur in the Ferriby Chalk of Suffolk. These are the Totternhoe Stone, around the middle of the formation, and the Nettleton Stone, slightly higher in the succession (Fig. 3). The Totternhoe Stone, named after a locality in the Chilterns (see Shephard-Thorn *et al*., 1994), is a widely developed marker-bed in East Anglia and the Northern Province that appears to be the product of a short-lived fall and subsequent rise in sea level (Gale, 1995). It rests discordantly and with marked colour contrast on the eroded top of the underlying chalk, into which the coarse-grained greyish-brown sediment is typically piped down in *Thalassinoides* burrows. The erosion surface is locally strongly channellised and consequently the Totternhoe Stone ranges in thickness from less than one metre on platforms to many metres in the channels. The extent of this downcutting can be seen in the Ely-Ouse boreholes (Gallois, 1988, fig. 24). In the Stowlangtoft Borehole the Totternhoe Stone is a hard, gritty chalk, creamy and brownish-white, with pyrite, shell and fish debris and small brown phosphatic lumps. Locally, as in Ely-Ouse Borehole 2 (Gallois, 1988, pl. 6), there are basal concentrations of bored, glauconitised and phosphatised chalk pebbles. The Totternhoe Stone has a distinctive Middle Cenomanian (*Acanthoceras rhotomagense* Zone) macrofauna characterised by the bivalve *Oxytoma* and a diverse assemblage of small brachiopods (Wood & Bristow, 1990); locally it contains the belemnite *Praeactinocamax primus*. The Totternhoes Stone is overlain by a thin bed of hard chalk containing *Orbirhynchia mantelliana* and large poorly preserved ammonites. The Nettleton Stone, also seen in the Stowlangtoft succession, is a thin bed of very hard, locally gritty and phosphatic chalk belonging to the upper part of the *Acanthoceras jukesbrownei* Zone (Wood & Bristow, 1990). It is underlain by a thin, greyish-brown oyster-rich marl, the Nettleton Pycnodonte Marl, which can be correlated with the 'Pycnodonte Event' in the northern German succession (Ernst *et al*., 1983). In the Southern Province, the Nettleton Stone and its underlying marl equate with Jukes-Browne Bed 7 in the middle part of the Zig Zag Chalk Formation. Above the Nettleton Stone, the higher part of the succession (*Calycoceras guerangeri* Zone) comprises pale coloured, poorly fossiliferous chalks with a few thin shell-rich horizons of small oysters and inoceramid bivalves.

White Chalk Subgroup

The White Chalk Subgroup encompasses the remainder of the Chalk succession, from the erosion surface immediately below the Plenus Marls to the erosion surface delimiting the top of the Chalk Group. In this account we recognise the Holywell Nodular Chalk, New Pit Chalk, Lewes Nodular Chalk and Seaford Chalk formations. A widely developed, largely flintless chalk unit above the Seaford Chalk is named the Blakenham Chalk Member, and is currently assigned to the Newhaven Chalk Formation. This formation appears in its more normal development at Wells-next-the-Sea, on the north Norfolk coast, where it contains flint horizons and well developed marl seams. The Blakenham Member is succeeded by flint-rich, highly fossiliferous chalks seen locally in the Gipping Valley, and assigned to the basal part of the Culver Chalk Formation. The bulk of the Culver Chalk is unexposed in the Suffolk region, as is its contact with the youngest part of the White Chalk Subgroup, which belongs to the Portsdown Chalk Formation. The boreholes at Sizewell preserve down-faulted Portsdown Chalk assigned to the Pre-Weybourne, Weybourne and lowermost Beeston Chalk of Wood (1988).

Holywell Nodular Chalk Formation

At the base of the White Chalk Subgroup and Holywell Nodular Chalk Formation, the Plenus Marls Member forms a thinly developed, clay-rich marker bed, typically less than a metre thick in the Suffolk region (e.g. Stowlangtoft Borehole), and just a few centimetres thick in the Trunch Borehole [TG 2933 3455] in north Norfolk (Fig. 3). Clay-filled burrows can often be seen extending below a well marked basal erosion surface, cut by a short-lived sea-level fall. Above this there is a succession of alternating soft, greenish grey marls and paler, harder limestones, up to eight beds in the Southern Province but usually fewer in East Anglia. The marls contain a varied fauna of mainly brachiopods (*Orbirhynchia*, *Ornatothyris*, *Concinnithyris*) and bivalves (*Entolium*, *Inoceramus pictus*, *Oxytoma*, *Pycnodonte*), together with the belemnite *Praeactinocamax plenus* after which the unit is named, albeit it only ranges through part of the succession. From Ashwell (Hertfordshire) northwards, *Ornatothyris* appears as an important component of the Plenus Marls fauna, and its presence might indicate a relatively shallower-water depositional environment compared to areas further south (Hopson *et al*., 1996). Rare ammonites demonstrate correlation with the Upper Cenomanian *Metoicoceras geslinianum* Zone. Although relatively thin in Suffolk, the Plenus Marls form a distinct and easily identifiable inflection on borehole geophysical logs, particularly gamma logs (Fig. 4).

In the latest Cenomanian and Early Turonian, sea levels began to rise rapidly, flooding many of the land areas and reducing the influx of clay-rich material. Chalk sedimentation radically expanded across these newly flooded shelf areas, blanketing them with chalk deposits. The start of this process is marked by the highest part of the Plenus Marls and the overlying part of the Holywell Nodular Chalk. Immediately above the Plenus Marls is a thin interval of hard, nodular, relatively poorly fossiliferous white limestone, named the Melbourn Rock after the locality at which it was first described in south-west Cambridgeshire. The Melbourn Rock is up to 2 m thick in Suffolk and forms a topographical feature that is valuable for mapping, seen between Worlington and Mildenhall; Mildenhall itself is sited on a low rise formed by the Melbourn Rock (Wood & Bristow, 1990). The Stowlangtoft Borehole shows several metres of richly shelly strata above the Melbourn Rock, with abundant remains of inoceramid bivalves in hard, nodular chalk with thin marls. The inoceramid bivalves almost exclusively comprise species of *Mytiloides*, which define the basal Turonian *Mytiloides* spp. Zone. This succession also typically contains brachiopods (*Orbirhynchia* and *Concinnithyris*) echinoids (*Conulus*) and occasional large ammonites (*Lewesiceras peramplum* and the zonal index *Mammites nodosoides*). In Ely-Ouse Borehole 2 [TL 7008 6976], nodular flints occur at the top of these bioclastic chalks, analagous with the position of the Glyndebourne Flints in Sussex (Mortimore & Pomerol, 1996), but in the Stowlangtoft Borehole the entry of flint is some 22 m higher in the succession, within the overlying New Pit Chalk Formation (Wood & Bristow, 1990). This bioclastic nodular chalk can also be identified as a distinct interval on borehole geophysical logs across East Anglia (Woods & Chacksfield, *in press*) and, together with the underlying Plenus Marls, forms an interval about 12 m thick in the Stowlangtoft Borehole.

New Pit Chalk Formation

Above the Holywell Nodular Chalk, the lithological change to firm or moderately hard, mostly smooth-textured chalk, signals the presence of the New Pit Chalk formation. At some levels there are nodular and shell-rich intervals, and horizons of nodular flints appear more consistently in the higher part of the succession. Fossils mainly comprise inoceramid bivalves, especially *Inoceramus cuvieri* and *I. lamarcki*, as well as the small zonal index brachiopod *Terebratulina lata*.

In the Stowlangtoft Borehole and Ely-Ouse Borehole 2 there are some atypical lithological features, including erosion surfaces overlain by chalk pebbles, and intervals of glauconitised chalk clasts; features that appear to be related to synsedimentary rejuvenation of deep basin structures that cause thinning of the New Pit Chalk succession across the northern part of Suffolk (Woods & Chacksfield, *in press*). In the Stowlangtoft Borehole, the New Pit Chalk is about 30 m thick, compared to 55 m in a borehole at Bartlow (Cambridgeshire), a few kilometres south-west of the Suffolk region (Woods & Chacksfield, *in press*). Two widespread marl seams are named the Methwold Marl, at or near the base of the succession, and the Pilgrims' Walk Marl, in the higher part of the succession, both conspicuous on borehole gamma and borehole resistivity logs. At Bartlow there is also geophysical log evidence for a least four further significant marl seams in the New Pit Chalk between the Methwold and Pilgrims' Walk Marl, possibly represented by records of thin, wispy marls in the condensed Stowlangtoft succession (Bristow, 1990, Appendix 2).

Lewes Nodular Chalk

The Lewes Nodular Chalk is typically hard, nodular, flint-rich chalk, with thin marl seams and sporadic iron-stained and/or glauconitised nodular chalks and hardgrounds. In Suffolk, application of this formation is problematic in terms of lithofacies; typical Lewes Nodular Chalk is certainly present, but the lowest and highest parts of the formation as defined by marker-bed correlations, contain unusually soft, smoother-textured chalk. Future work may result in a modified lithostratigraphy for this part of the Chalk Group.

For the purpose of this work, the base of the Lewes Nodular Chalk in Suffolk is taken at the Mount Ephraim Marl. This marl is correlative with the volcanogenic Southerham Marl 1, which occurs a short distance above the base of the Lewes Nodular Chalk in the Southern Province (Mortimore, 1986; Mortimore & Wood, 1986). In Suffolk, the Mount Ephraim Marl is a distinctively thick marl (c. 0.1 m), containing an abundance of the large agglutinating foraminifer *Labyrinthidoma* (formerly *Coscinophragma*) which can be matched with a similar abundance in Southerham Marl 1. Where seen in exposures at Brandon [TL 789 861], the chalk associated with Mount Ephraim Marl is locally hard and gritty, with sponge-rich horizons and sporadic nodular flints. Fossils are mainly the bivalves *Inoceramus cuvieri* and *Inoceramus perplexus*.

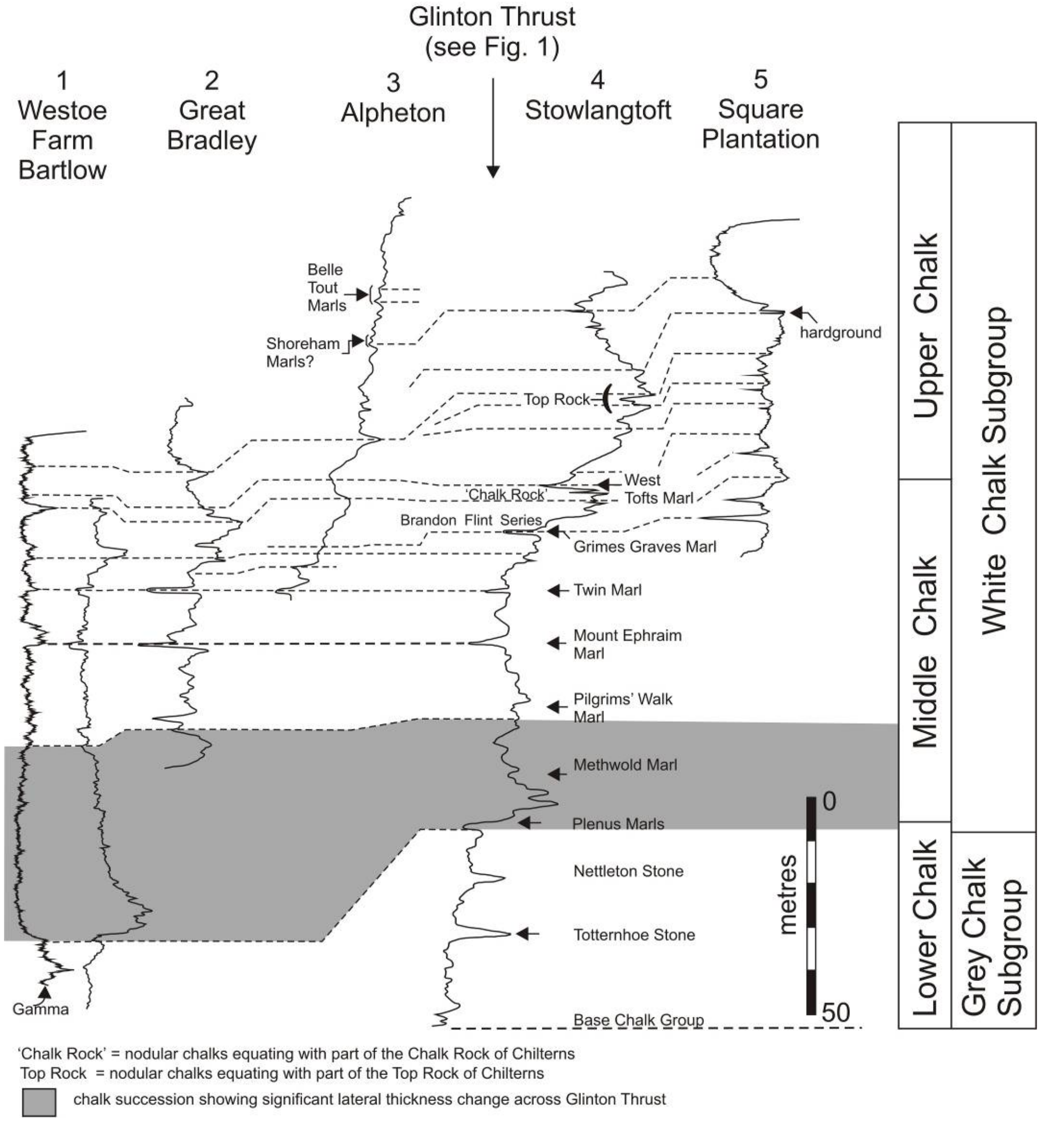

Fig. 4. Correlation of borehole resistivity logs in the Chalk Group showing lateral continuity of marker beds and thinning of the lower part of the White Chalk Subgroup (Holywell and New Pit Chalk formations) in the Stowlangtoft Borehole (borehole locations shown in Fig 1). For explanation of basis for borehole correlations see Woods (2006) and Woods & Chacksfield (*in press*).

In a pit at Great Chesterford [TL 515 428], in Cambridgeshire, the chalk immediately beneath the Mt. Ephraim Marl yielded a rich fauna of well preserved flint-filled inoceramid bivalves and echinoids (Mortimore & Wood, 1986). Further distinctive marl seams occur above the Mount Ephraim Marl, including the Twin Marls and Grimes Graves Marl, all forming distinctive and easily recognisable inflections on borehole geophysical logs (Pattison *et al*., 1993, fig. 13; Woods & Chacksfield, *in press*). The Twin Marls and Grimes Graves Marl equate with the volcanogenic Caburn Marl and Bridgewick Marl 1 in the stratotype Sussex succession of Mortimore (1986), and, with Southerham Marl 1, are typically associated with hard, nodular chalk in the Southern Province; borehole resistivity log profiles also sharply differentiate the chalk containing these marls from the underlying New Pit Chalk. Whilst this is similarly true for the Grimes Graves Marl in Suffolk, the chalk containing the lower marl seams is significantly softer in Suffolk, as demonstrated by the lack of differentiated borehole resistivity log profiles (Fig. 4; Woods & Chacksfield, *in press*).

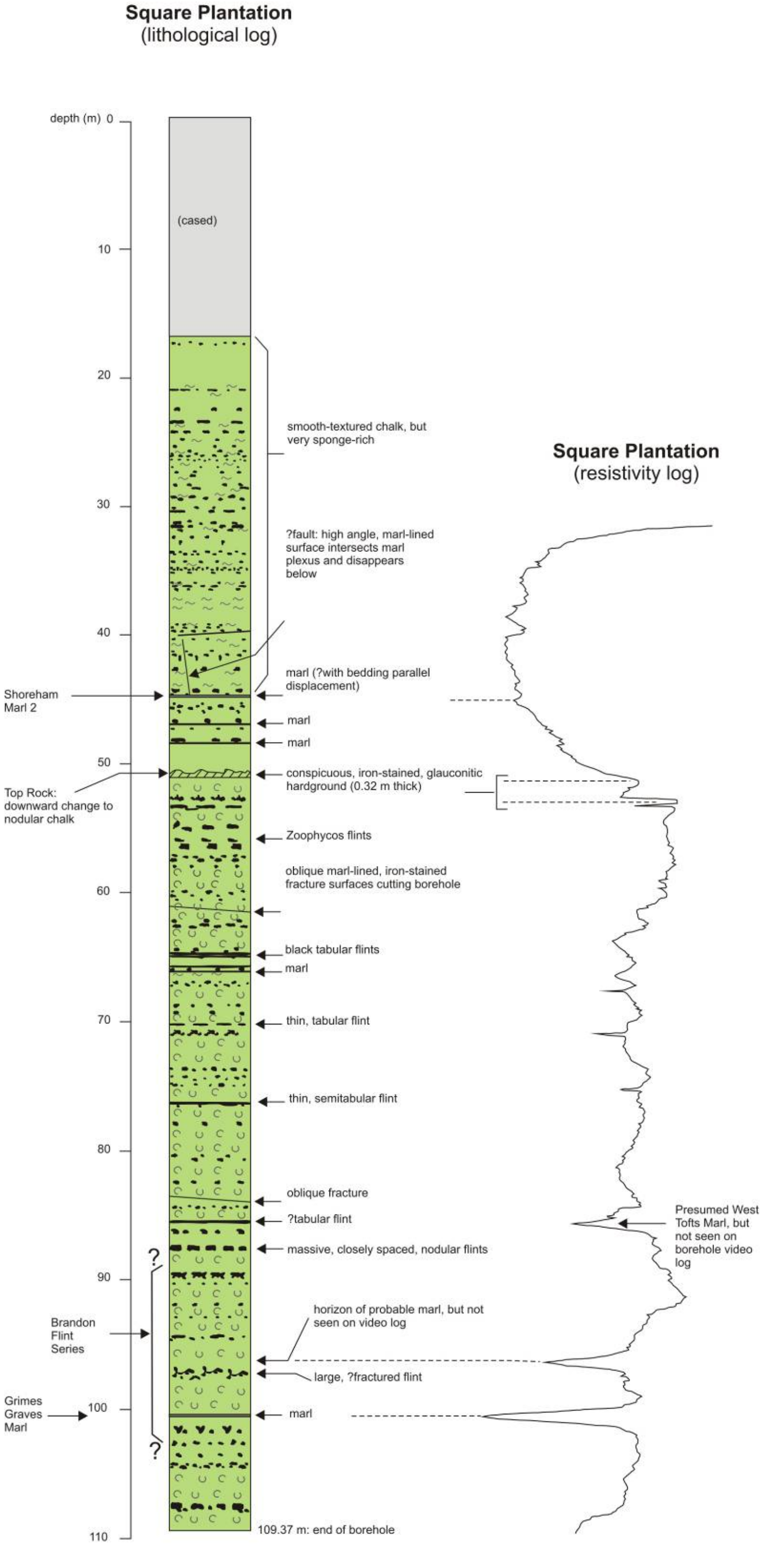

Fig. 5. The Chalk succession in the Square Plantation Borehole and correlation with borehole resistivity log. Lithological log derived from interpretation of borehole video log data.

Above the Twin Marls, a distinctive flint-rich interval, about 15 m thick, appears in the chalk succession in Suffolk and south Norfolk, associated with the upward development of hard, nodular chalk. It is named the Brandon Flint Series after the sequence described from prehistoric flint mines at Grimes Graves near Brandon [TL 818 898] (Skertchley, 1879; Mortimore & Wood, 1986, fig. 2.5). The flints comprise large nodular and tabular forms, and it is within this flinty interval that the Grimes Graves Marl occurs (Mortimore & Wood, 1986; Fig. 3). The succession is very similar to, and correlative with, the tabular flint-rich interval containing the North Ormsby Marl in the Northern Province and the flinty chalk associated with the Bridgewick Marls in the Southern Province (Mortimore & Wood, 1986, fig. 2.3; Fig. 3A). Both the Grimes Graves Marl and Brandon Flint Series occur in the lower part of the Square Plantation Borehole, east of Thetford, overlain by about 40 m of hard, nodular chalk with common bands of nodular flint as well as several horizons of tabular flint (Fig. 5).

The feature-forming character of the Brandon Flints, and their approximate coincidence with the base of the *Plesiocorys* (*Sternotaxis*) *plana* Zone, made them a useful replacement for the Chalk Rock in mapping the base of the traditional Upper Chalk. Across East Anglia, the Chalk Rock is generally represented by a thin, weakly developed hardground or one or more horizons of iron-stained nodular chalk, in contrast to its much stronger development in the Chilterns and the Berkshire Downs. Around Bury St Edmunds, it comprises about 0.3 m of hard, yellow, nodular chalks a short distance above the Brandon Flint Series, as seen near Moulton [TL 697 632, TL 703 648]. It has a distinctive fauna of originally aragonite-shelled molluscs, preserved as moulds, especially ammonites indicative of the *Subprionocyclus neptuni* Zone of the standard ammonite zonal scheme. However, further south near Sudbury, borehole resistivity log correlations suggest that the Chalk Rock may be more strongly developed in the subsurface hereabouts (Pattison *et al.*, 1993, fig. 13). In East Anglia, the Chalk Rock equates with the highest of a series of hardgrounds (Hitch Wood Hardground) that variably comprise the Chalk Rock where more completely developed in the Chilterns (Bromley & Gale, 1982).

The *plana* Zone succession above the Chalk Rock includes fossiliferous, highly flinty chalk, seen in the railway cuttings near Higham [TL 7469 6604], west of Bury St Edmunds. Even higher flinty chalk in this zone was exposed in cuttings on the A45 at Barrow Heath [TL 777 661 to 783 661], where they yielded a rich fauna including unusually large *Micraster*. These beds grade up into the Top Rock, a 0.4 m thick bed of intensely indurated yellow-stained chalk (chalkstone) penetrated by a *Thalassinoides* burrow system and terminating in a glauconitised convolute hardground overlain by glauconitised pebbles (Wood & Bristow, 1990, fig. 9; Fig. 3B). The Top Rock extends from the Chilterns north-eastwards into East Anglia, and is also seen in a chalk pit at Dalham [TL 7255 6243]. However, in the Stowlangtoft Borehole, east of Bury St. Edmunds, the Top Rock almost completely disappears and is possibly represented by closely-spaced, iron-stained sponge-bearing chalks (Wood & Bristow, 1990). Where typically developed, the Top Rock represents a condensed equivalent of the lower part of the *Micraster cortestudinarium* Zone, and is more fossiliferous in western Suffolk than in most localities further south. The fauna includes abundant hexactinellid sponges and the echinoids *Echinocorys* cf. *gravesi* and *Micraster cortestudinarium*, all preserved as glauconitised pebble-fossils resting on the hardground. Of particular importance at the top of the chalkstone are variably phosphatised inoceramid bivalves (predominantly various species of *Cremnoceramus*) which indicate the terminal part of the Turonian and lower part of the Coniacian. In the Square Plantation Borehole (Fig. 5), an iron-stained and glauconitic hardground might represent a relatively younger stratigraphical development of the Top Rock, based on its close proximity to Shoreham Marl

2 (see below), or alternatively is an unrelated hardground locally developed near the top of the formation.

The higher part of the *M. cortestudinarium* Zone is poorly exposed across Suffolk, but where locally seen west of Bury St Edmunds, for example at Dalham, showed hard, nodular chalk above the Top Rock passing upwards into rather featureless, finer-grained, flinty chalk (Wood & Bristow, 1990, fig. 9; Fig. 3B). The total thickness of Lewes Nodular Chalk (as defined herein) seen in the Stowlangtoft Borehole is about 78 m.

Seaford Chalk Formation

Borehole geophysical logs near Sudbury (Pattison *et al*., 1993, fig. 13) suggest the presence of both the Shoreham Marls and Belle Tout Marls; the former marking the base of the Seaford Chalk Formation and the *Micraster coranguinum* Zone in Sussex, and the latter characterising the lower part of the formation in that area (Fig. 3). Slightly higher in the succession, an old chalk pit at Euston [TL 89453 777359 to TL 89528 77481] (Figs 3, 6), between Bury St Edmunds and Thetford, exposes soft, smooth-textured, flint-rich chalk, with abundant large shell fragments of inoceramid bivalves in the lower part. These mainly comprise *Platyceramus* and *Volviceramus*, and are particularly concentrated below a semitabular flint near the base of the section. This flint represents the Seven Sisters Flint, a marker-bed in the lower part of the Seaford Chalk in the stratotype Sussex succession, which is likewise underlain by inoceramid-rich Chalk and may correlate with the giant Eppleworth Flint in the Northern Province Burnham Chalk Formation (Wood in Gaunt *et al*., 1992; Fig. 3). A similar concentration of *Volviceramus* was recorded in the lower (Middle Coniacian) part of the *M. coranguinum* Zone in the Stowlangtoft Borehole (Wood & Bristow, 1990, fig. 7), as well as in numerous localities in and around Bury St. Edmunds.

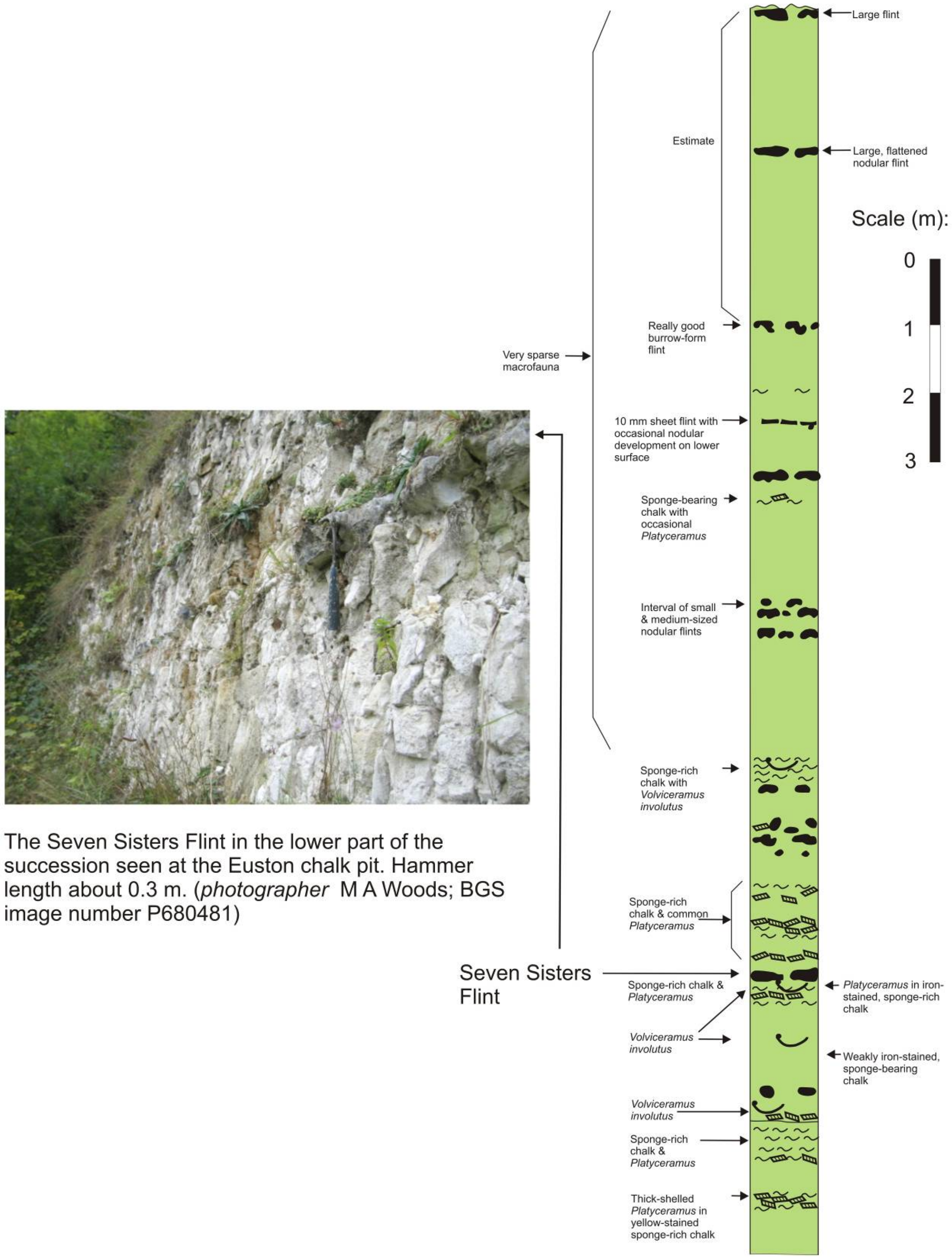

Fig. 6. The Chalk succession at Euston chalk pit [TL 89453 77359 to 89528 77481] between Bury St Edmunds and Thetford.

Sections in the upper (Santonian) part of the *M. coranguinum* Zone occur at Horringer Court [TL 837 628], south-west of Bury St Edmunds, where the chalk was worked in extensive underground galleries, and near Ixworth [TL 934 707], to the north-east (Wood & Bristow, 1990). The faunas include the brachiopods *Gibbithyris ellipsoidalis* and *Kingena lima*, and the echinoids *Micraster*, *Echinocorys*, *Conulus albogalerus*, *Temnocidaris (Stereocidaris)* *sceptrifera* and *Tylocidaris clavigera*. The highest part of the *coranguinum* Zone is exposed in the Stowlangtoft Quarry [TL 9475 6882]. Here, a semi-continuous flint underlain by shell fragments of inoceramid bivalves (*Cordiceramus* and *Platyceramus*) near the floor of the eleven-metre section (Wood & Bristow, 1990, fig. 10) correlates with the Whitaker's 3-inch Flint, a distinctive tabular flint marker that is widely seen in coeval chalk in the North Downs and chalk quarries in the lower Thames valley (Robinson, 1986)**.** A well developed yellow sponge bed, about 1 m higher, overlain by chalk with a rich fauna including *Conulus albogalerus*, *Echinocorys* and *Micraster,* could then equate with the Barrois Sponge Bed that occurs in some depositional settings near the top of the Seaford Chalk Formation in the Southern Province succession. On this basis, combined data from the Stowlangtoft Borehole and Stowlangtoft quarry section suggests that the Seaford Chalk is about 55 m thick hereabouts. Further south, in the Popsbridge Borehole [TL 97060 33890] near Nayland (Fig. 2), a hardground at 45.7 m depth might also equate with the Barrois Sponge Bed; it is overlain by basal Newhaven Chalk belonging to the *Uintacrinus socialis* and ?*Marsupites testudinarius* zones (Ellison & Lake, 1986).

Newhaven Chalk Formation

Typically, Newhaven Chalk is characterised by the regular development of marl seams and horizons of nodular flint, as seen at many localities across southern England, and also in north Norfolk at Wells-next-the-Sea and in the Trunch Borehole (Wood *et al*., 1994). However, in Suffolk, the latest Santonian and earliest Campanian part of the Newhaven Chalk is almost flintless, with inconspicuous marls represented by thin wisps rather than distinct seams. This chalk, more than 60 m thick locally and belonging to the topmost *M. coranguinum*, *U. socialis*, *M. testudinarius* and *Offaster pilula* zones, is generally very soft and fine grained. It can be seen in the south of the Suffolk region, at the Victoria chalk pit, Sudbury [TL 8793 4175], where it is inferred to be in the *U. socialis* and lower *M. testudinarius* Zone (Pattison *et al*., 1993), and in small scattered exposures at Monks Eleigh [TL 9649 4718] and Nedging Mill [TL 9649 4718] (Fig. 2). The most extensive development of this facies occurs further east in the Gipping Valley, near Ipswich, and has been designated the Blakenham Chalk Member (Woods *et al*., 2007) (Figs 2, 3A, 3B). It is best seen in the large disused chalk pit at Great Blakenham [TM 1161 4986], but other good exposures occur at Little Blakenham [TM 1108 4899, TM 1086 4910] and Needham Market [TM 0940 5395] (Fig. 7), and there are numerous borehole records through this interval in the Ipswich area (Woods *et al*., 2007; Fig. 8). The weakly developed marls in the Ipswich succession suggest affinity with the Newhaven Chalk Formation of the Southern Province. The fauna includes small calyx plates of the zonal index crinoids, together with brachiopods, oysters (especially *Pseudoperna boucheroni*), the echinoid *Conulus albogalerus* and the belemnite *Actinocamax verus*. A coarse-grained, shell-rich chalk interval in the lower part of the *O. pilula* Zone in the Blakenham Member of the Ipswich district, can be matched with coeval bioclastic facies in the Trunch Borehole (300–307.35 m depth) in north Norfolk (Wood *et al*., 1994), and with similar coarse-grained chalks (termed Grobkreide facies) at this stratigraphical level in Germany (Woods *et al*., 2007).

Fig. 7. Flint-free Blakenham Chalk Member being excavated at the Needham Market Chalk quarry, in the Gipping Valley, north-west of Ipswich. (photographer M. A. Woods; BGS image number P584984).

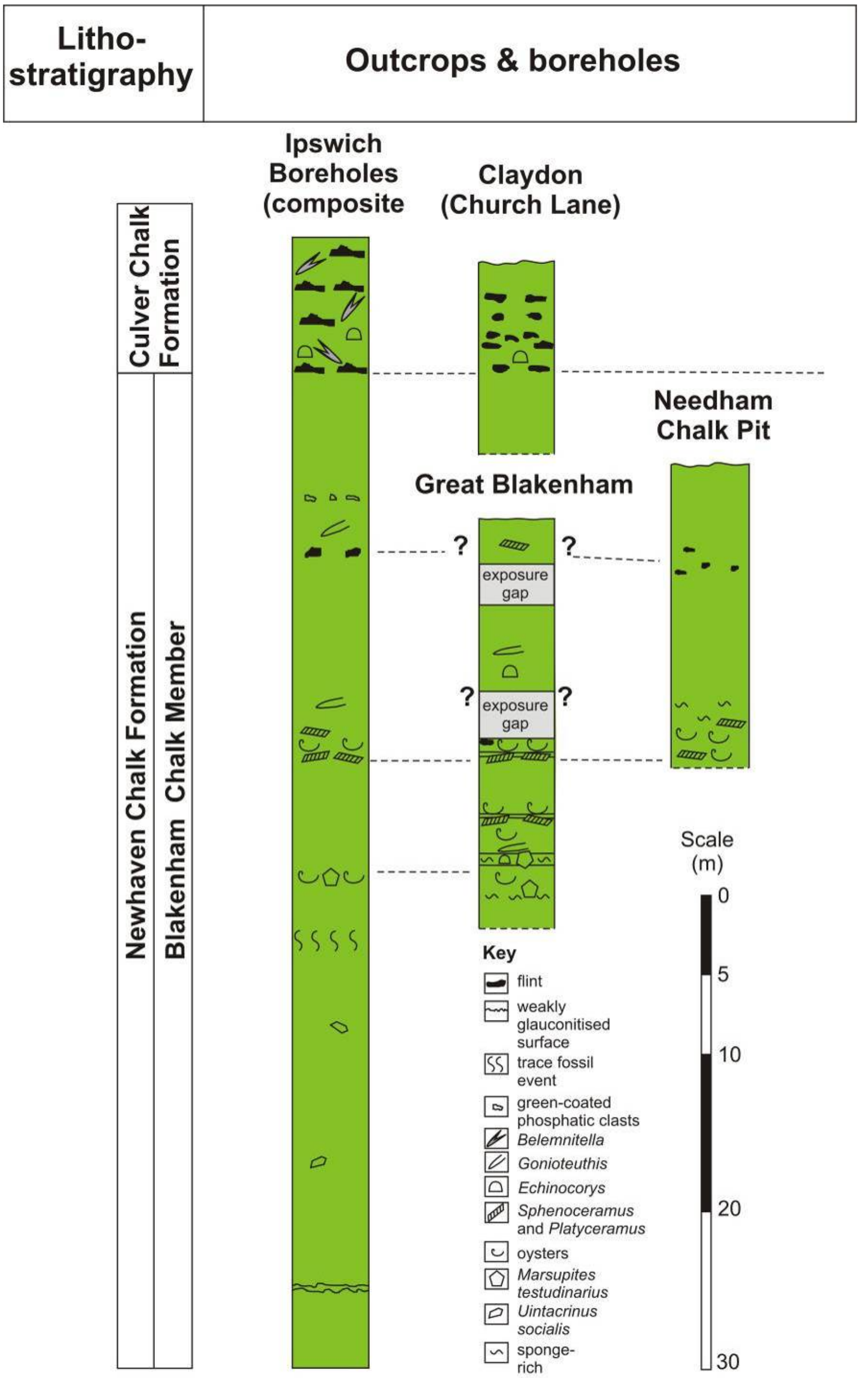

Fig. 8. Sections and boreholes through the Blakenham Chalk Member in the Gipping Valley and Ipswich district. Based on a figure by Woods *et al*. (2007). For location details see Figs 1 and 2.

Culver Chalk Formation

The highest outcropping chalk in the Suffolk area is seen in the Gipping Valley at the Claydon (Church Lane) pit [TM 1363 4966], where a few metres of soft, flint-rich chalk belonging to the Lower Campanian *Gonioteuthis quadrata* Zone occur above the Blakenham Chalk (Fig. 8). Lithologically this flinty chalk resembles the lower part of the Culver Chalk Formation of Sussex, with which it is coeval (Woods *et al*., 2007). The diverse macrofossil fauna from this interval at the top of the Project Orwell boreholes includes the echinoids *Echinocorys* and *Micraster*, the small coral *Desmophyllum regularis* and the belemnite

Belemnitella. Some historical accounts of this succession (Boswell, 1927; Brydone, 1932) assigned it to the *Belemnitella mucronata* Zone, but the *Belemnitella* records actually represent *B. praecursor*, from the *Hagenowia blackmorei* Subzone at the base of the *G. quadrata* Zone (Woods *et al*., 2007). It is noteworthy that Markham (1967) recorded *Gonioteuthis* from the highest beds at the Claydon (Church Lane) pit and suggested that, in the Gipping Valley, beds with *Belemnitella* are succeeded by beds with *Gonioteuthis*.

Nothing is known about the remainder of the *Gonioteuthis quadrata* Zone succession in Suffolk.

Portsdown Chalk Formation

At Sizewell, a few kilometres east of Saxmundham, boreholes have proved up to 60 m of Chalk below 80 m of Tertiary strata. This chalk appears to occur in a down-faulted basin, and is mainly soft and smooth-textured, with common thin marl wisps, marly chalk and marl-infilled burrows. Parts of the succession have a distinctly mottled appearance, probably reflective of extensive bioturbation, which also includes well developed *Zoophycos*-rich horizons. There are sporadic horizons of nodular flint, and three hardgrounds in the upper part of the succession are associated with locally hard, phosphatised and glauconitised chalk. This lithofacies is fairly typical of the lower, marl-rich part of the Portsdown Chalk Formation as developed in the Southern Province, although the diffuse distribution of marl in the Sizewell succession (rather than being concentrated into marl seams) is unusual, and perhaps a product of the local depositional/tectonic setting.

Only the highest 30 m of this succession have been studied in detail and no biostratigraphical information is available from the relatively dark coloured and marl-rich underlying beds. The core examined can be assigned to the lower part of the Upper Campanian traditional *Belemnitella mucronata* Zone. The lowest 18 m terminate upwards in an irregular glauconitised hardground and correlate with the Pre-Weybourne Chalk of Wood (1988). Macrofossils include *Belemnitella* cf. *mucronata, B.* cf. *praecursor, Kingena pentangulata, Gyropleura inequirostrata* and *Pseudolimea granulata*, with sporadic abundances of *Cretirhynchia* ex gr. *lentiformis* and *Hyotissa? semiplana*. The hardground is associated with common sponge remains, some phosphatised. Above this, about 8 m of chalk are assigned to the Weybourne Chalk, with a macrofauna that includes *Cretirhynchia* ex gr. *lentiformis* and *Cretirhynchia woodwardi*, the latter being restricted to this subdivision. The top of the Weybourne Chalk is marked by a pair of closely spaced glauconitised hardgrounds, equated with the Catton Sponge Bed (Mortimore *et al*., 2001, fig. 4.26) seen inland around Norwich and on the Norfolk coast, as well as in the Trunch Borehole (Wood *et al*., 1994). These hardgrounds reflect a major inter-regional regressive event, the *polyplocum* regression ,which is expressed by correlative hardgrounds in Northern Ireland, Belgium and the Netherlands. The chalk above the hardground pair is devoid of marl and is relatively massive, with numerous glauconitised phosphatic clasts. It is richer in macrofossils than the beds below, the fauna including common sponge remains, the ammonites *Baculites* and ?*Nostoceras* (*Bostrychoceras*), small gastropods and *Cretirynchia arcuata*. These highest beds are correlated with the basal part of the Beeston Chalk of the Norfolk coast succession. A rich macrofauna from up to 2 m of Chalk cored beneath 38 m of Tertiary strata in the BGS Halesworth Borehole [TM 4178 7627] (Fig. 2) also suggests a level within the Beeston Chalk (Moorlock *et al*., 2000).

Intra-Cretaceous tectonic impacts on the Chalk Group of Suffolk

At least three well established phases of intra-Cretaceous tectonic disturbances ('Subhercynian tectonic phases') have affected the Chalk Group in Britain and the wider European region (Mortimore & Pomerol, 1997; Mortimore *et al*., 1998), and these may also have played a role in shaping the development of the Chalk Group in Suffolk. These structural disturbances were assumed to be direct precursors to later (Miocene) Alpine tectonism, but recently Kley & Voigt (2008) showed that intra-Cretaceous basin inversion in central Europe was related to a change in the relative motion between the European and African plates, unrelated to early Alpine orogenic movements. This change established a compressional stress regime with SSW–NNE-directed thrusting and folding and reactivation of basement structures. The new stress regime developed across Europe, affecting the relatively weak, structurally fragmented lithosphere between the African and Baltic cratonic blocks, and is the likely cause of the Subhercynian tectonic events.

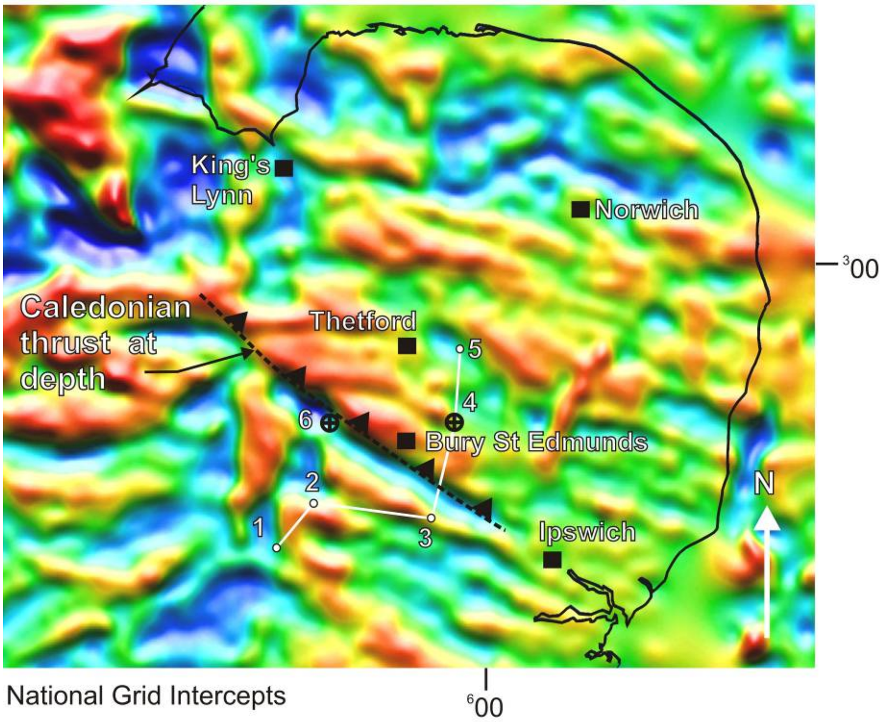

Fig. 9. Residual Bouguer gravity anomaly map of the Suffolk region and adjoining areas, showing line of borehole correlation in Fig. 4 and position of major Caledonian thrust at depth. Red denotes positive anomalies and blue negative anomalies. Based on a figure by Woods & Chacksfield (*in press*). Borehole and locality details: 1 Westoe Farm, Bartlow [TL 6011 4501]; 2 Great Bradley [TL 6720 5427]; 3 Alpheton [TL 9041 5060]; 4 Stowlangtoft [TL 9475 6882]; 5 Square Plantation [TL 9560 8336]; 6 Ely-Ouse Borehole 2 [TL 7008 6976].

Correlations of borehole geophysical logs in the Chalk Group across East Anglia reveal a sharp lateral change in thickness of part of the Turonian succession in the Stowlangtoft Borehole (Fig. 4) which is also maintained in other boreholes northwards (Woods & Chacksfield, *in press*). Regional gravity data suggests that this might be due to Early Turonian reactivation of a thrust fault in the Caledonian basement just south-west of Bury St Edmunds (Fig. 9). Some lithological data to support this interpretation comes from Ely-Ouse Borehole

2 [TL 7008 6976], located close to the gravity lineament produced by the buried thrust. Here, the lowest 20 m of the *T. lata* Zone, immediately above shell-rich chalk inferred to equate with the Holywell Nodular Chalk Formation, contains common horizons of large (50–100 mm) green and buff-coated nodules (Wood & Bristow, 1990, p. 21). These records suggest the presence of mineralised hardgrounds and erosion surfaces with glauconite and phosphate, and are below the expected horizon of the Chalk Rock and Top Rock at which levels these features might otherwise be expected.

Another striking feature of the Suffolk succession is the apparent widespread development of flintless chalk (Blakenham Member) in the Late Santonian and Early Campanian. The age of this chalk is broadly coincident with the timing of one of the main Subhercynian tectonic phases (Wernigerode Phase; Mortimore & Pomerol, 1997; Mortimore *et al*., 1998). Cornwell *et al.* (1996) showed that deep-seated basement faults probably controlled the margins of a 45 km long ridge of Chalk (Sudbury–Bildeston Ridge) in Suffolk that extends as far north as Eye (Fig. 1). A similar, more substantial fault-bounded Chalk ridge (Framlingham Ridge) occurs further east (Bristow, 1983; Cornwell *et al*., 1996; Fig. 1). The basement is elevated by about 100 m beneath the Sudbury–Bildeston Ridge, the alignment of which crosses the northern end of the Gipping Valley at Needham Market (Bristow, 1983, fig. 2; Cornwell *et al*., 1996; Fig. 1). Traced southwards, the alignment of the Framlingham Ridge intersects the Gipping Valley. It is tempting to speculate that prior to the faulting that formed the Chalk ridges, the Gipping Valley–Ipswich area was part of a structural high bounded by ancient fault lines that perhaps, through short-lived rejuvenation during Wernigerode Phase tectonism, influenced the local style of chalk sedimentation. Northwards, as the northern margin of the buried London Platform is crossed in the area around Diss (Gallois & Morter, 1982), there is evidence for increasing flint in strata equivalent to the Blakenham Member (Mathers *et al*., 1993).

Engineering geology

East Anglia was the birthplace of the modern approach to the engineering geology of the Chalk. Just across the Suffolk border at Mundford, in south-west Norfolk, a ground investigation at the U.K.'s candidate site for a possible CERN Proton Accelerator set the standard for many years for classifying Chalk for engineering purposes (the Mundford Grades, Ward *et al*., 1968). Subsequently, Wakeling (1970) investigated the relationship of the borehole Standard Penetration Test (SPT) to the Mundford Grades at the CERN site. The Mundford Grades, and their extrapolated SPT 'N' values have been used widely ever since in Chalk engineering. It was, however, never the intention of Ward *et al.* (1968) that the Mundford Grades should be used without critical appreciation of the local geology (e.g. Burland, 1990). Ground engineering projects in the Chalk away from the Mundford site illustrated the non-linear depth changes in chalk strength, fracture frequency and fracture aperture (e.g. Lord *et al*., 2002; Mortimore, 2012). To overcome these problems the CIRIA Grades have been introduced (Lord *et al*., 2002) as the new standard, and these separately record fracture aperture, fracture frequency and the field tests required to describe intact dry density (IDD) as a proxy for strength.

Similarly, the simple extrapolation of SPT to Mundford Grade was questioned (Mortimore & Jones, 1989), and at the Bury St Edmunds sugar silo sites was investigated by over-coring of SPT boreholes to determine the specific lithologies or structure that may have been controlling the SPT 'N' values (Mortimore *et al*., 1990). Here, the influence of flint bands on the SPT results was revealed (Figure 10), and the relationship of chalk grades described from cores bore very little similarity to Chalk Grades obtained from SPT ‘N’ values. These results suggest that the SPT values should be treated separately from a Grade Classification.

The site investigations at Mundford and Bury St Edmunds, combined with geological and engineering geology logging at Grimes Graves (Mortimore, 1979), provided invaluable information on the stratigraphy, structure and sedimentology of the Chalk in north-west Suffolk and south-west Norfolk. In the Mundford investigations, Gallois (in Ward *et al*., 1968) illustrated the stratigraphy (Fig. 11) and showed that the ‘high-strength’ high density Mundford Grade I chalks were associated with the lithological unit then known as the Melbourn Rock. In the overlying equivalent of the New Pit and Lewes Chalk formations Gallois (in Ward *et al*., 1968) recognised the presence of intraformational channels (Gallois pers. comm.; Ward *et al.*, 1968, fig. 5a) which locally cut out marker beds such as the Twin Marls. In addition, the Mundford investigations illustrated the presence of local low amplitude folding in the Chalk.

Correlations between the Mundford Site and the Bury St Edmunds Sugar Silo boreholes (Fig. 11) indicated that there were lateral changes in thickness and the degree to which nodular chalks and/or hardgrounds were developed, and changes in their stratigraphic range. It seemed likely that the nodular chalk layers characteristic of the Lewes Chalk present at Bury St Edmunds possibly died-out northwards into south Norfolk.

Both the Mundford and Bury St Edmunds investigations illustrated the relationship between Chalk Grade and mechanical properties (e.g. Ward *et al*., 1968, table 6), especially in relation to ground settlement beneath cyclically loaded foundations. The CERN site at Mundford was located with the simplicity of the underlying geology in mind, particularly the low angle of stratal dip, relatively uniform and consistent lithologies, and lack of Quaternary palaeovalleys cut into the Chalk.

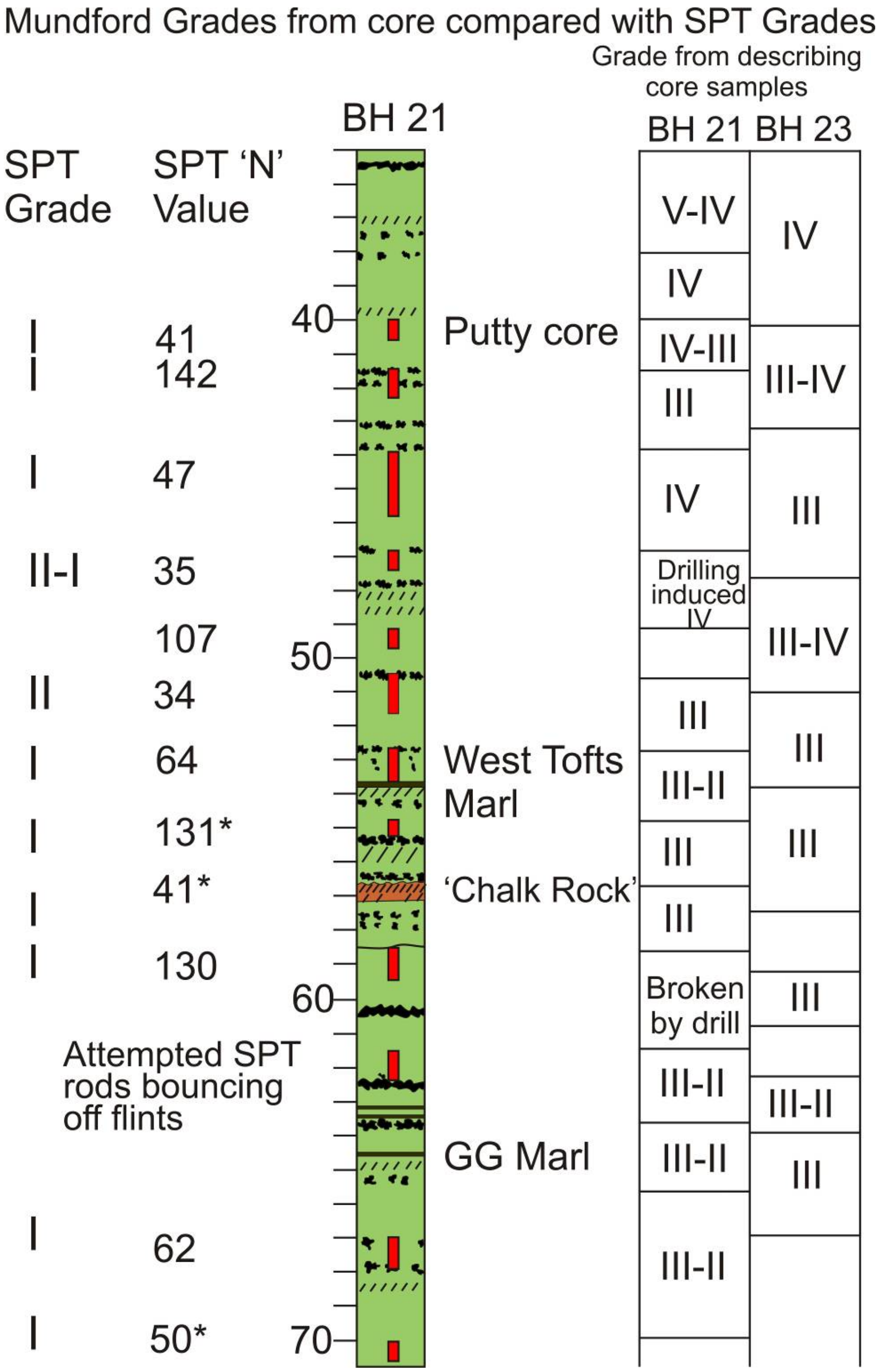

Fig. 10. Differences in Mundford Grades obtained from describing cores compared with those extrapolated from SPT 'N' values in Bury St Edmunds Borehole 21 (nearby Borehole 23 grades added to show consistency from core descriptions). Borehole 21 over-cored the SPT intervals to also show the influence of flint bands on SPT results (based on Mortimore *et al.*, 1990). 50* indicates that the SPT was not completed by driving the rod to the full depth required. GG Marl = Grimes Graves Marl.

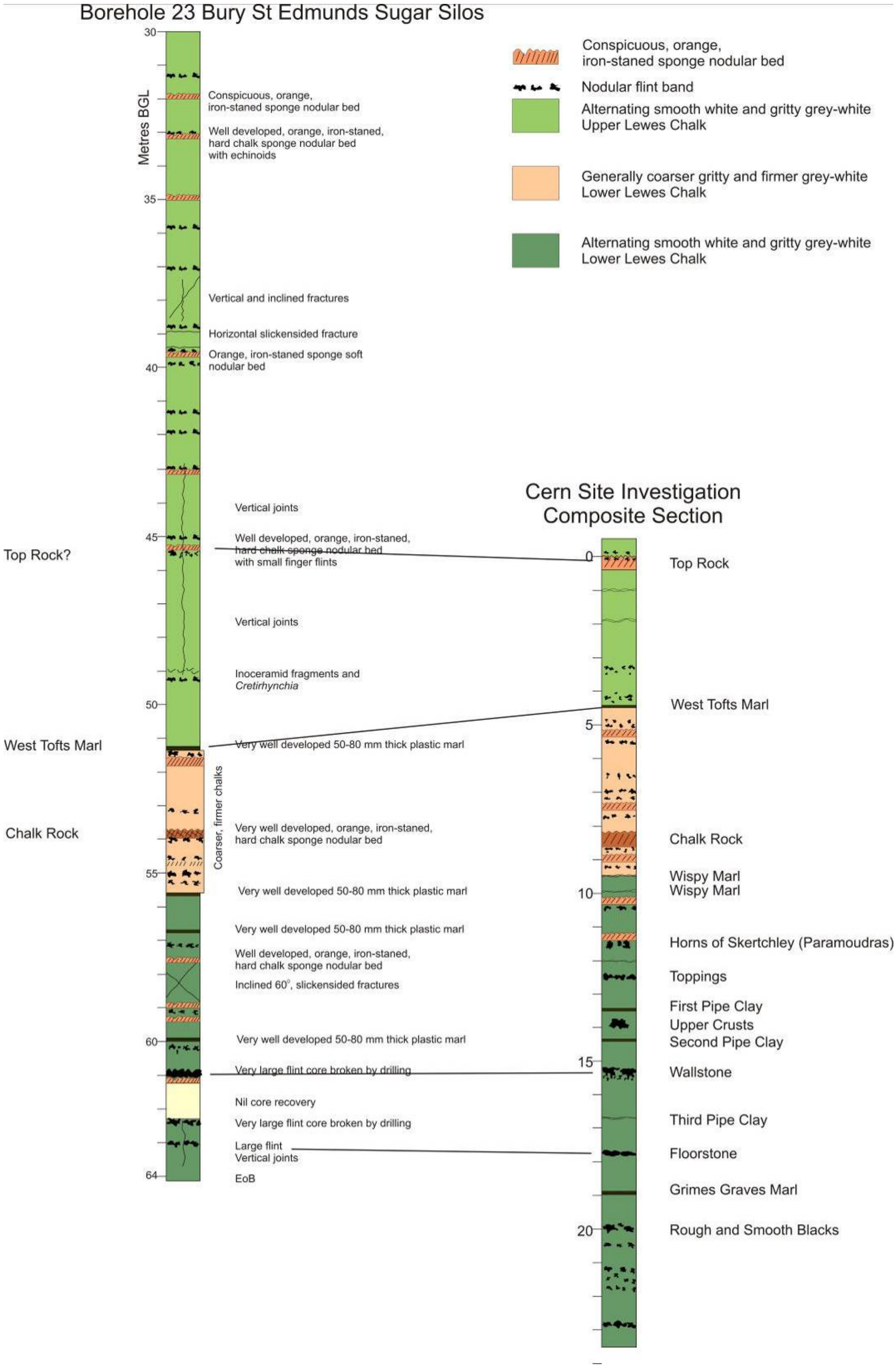

Fig.11. Comparison between the Mundford, Norfolk CERN site stratigraphy compared with Borehole 23 at Bury St Edmunds Suffolk showing lateral variations in the East Anglian ‘Chalk Rock’ interval and nodular chalks continuing upwards in the equivalent of the Lewes Chalk in Suffolk. (Based on Mortimore *et al*., 1990)

In contrast, the Bury St Edmunds silo site was adjacent to a probable subglacially cut valley (tunnel valley) into underlying Chalk. The sides and floor of the valley were found to contain 30–40 m of destructured chalk (Grade V of the Mundford Scale or Grade D of the CIRIA scale, Ground Engineering Report No. 830836, May 1981, 1.13). Rockhead or structured chalk was encountered at 13 m Below Ordnance Datum (BoD) creating a nearly 50 m high palaeo-river cliff adjacent to the site possibly inducing stress-relief valley-wards. Orientations of fractures recorded in trial shafts found that major joint sets trended NNW–SSE, N–S and E–W. The NNW–SSE set broadly paralleled the tunnel valley and the course of the River Lark running through Bury St Edmunds.

The Mundford and Bury St Edmunds investigations provided insights into a small part of the Chalk successions in Suffolk and to local ground conditions, particularly the presence of tunnel valleys and the orientations of fractures in the buried Chalk. Building the Project Orwell Storm Relief Tunnel in Ipswich (Anon, Tunnels and Tunnelling, September 1999, pp. 1–3) gave invaluable information from higher units in the Chalk and an insight into a further range of possible engineering conditions in the Chalk of Suffolk. At the start of this project the specific stratigraphy and lithology of the Chalk along the tunnel line was unknown. Cored boreholes yielded information suggesting there were horizons of pure white chalks without flints and several horizons with flints that could possibly be used as marker beds along the entire length of the tunnel. The generally flintless chalks yielded macrofossils from the cores that indicated that this Chalk belonged to the *Uintacrinus socialis*, *Marsupites testudinarius* and *Offaster pilula* zones, equivalent to the Newhaven Chalk Formation but without the marl seams and flint bands (Woods *et al*., 2007). This lithology had similarities with the Margate Chalk Member of southern England and was assigned to a new local member, the Blakenham Member (Woods *et al*., 2007). The overlying flinty chalk was assigned to the (flint-rich) Culver Chalk Formation of southern England as the rich macrofauna indicated the lower part of the *Gonioteuthis quadrata* Zone.

Several key geological risks that could influence tunnel stability and the performance of the Tunnel Boring Machine (TBM) were identified before tunnelling began. One of the risks related to flints in terms of their size, strength and continuity. During construction of Shaft Number 1 (Fig. 13) a band of large flints was encountered raising concerns about their continuity (the blue grey flints shown in Fig. 12A). Such flints would increase wear on the TBM cutters, TBM head and the spoil conveying system, and could prevent the TBM from staying at the correct horizon if present in the roof or floor of the tunnel. A research programme was initiated with the University of Brighton, part-funded by AMEC Tunnelling, to investigate the possibility of guiding the TBM through the Chalk using microfossils so that the flints could be avoided. Tim Wright was appointed as the researcher for the programme, and using samples from Shaft Number 1 and cores from the adjacent Borehole 3, a microfossil biostratigraphic scheme (Figs 12A, B) was developed and successfully employed throughout the construction of the entire length of the tunnel (Fig. 13), enhancing the production rate and reducing the risk to the TBM (Tunnels and Tunnelling, 1999).

Other risks to the tunnelling included the possibility that some of the Chalk may be isolated ice-rafted blocks surrounded by glacial sediments. One borehole at the far north-west end of the scheme (BH 66, Fig. 13), started in glacial sediments, passed through Chalk and then encountered glacial sediments again below tunnel invert. Ice-rafted blocks were not proved but their presence in the area must remain a possibility. Further risks were the possible presence of dissolution features and associated high groundwater flows, mixed face tunnelling and steering difficulties, particularly in structureless chalks (Fig. 13). As at Bury St Edmunds, the extent of structureless chalks, especially within and adjacent to tunnel valleys, was a concern.

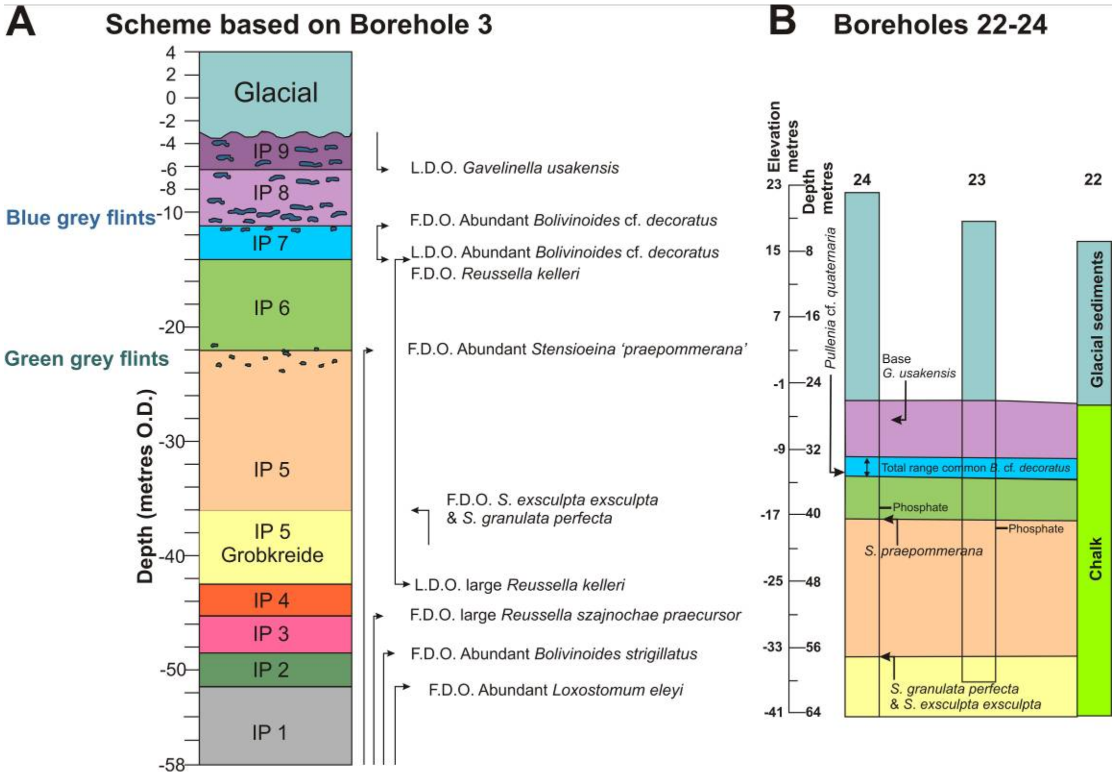

Fig. 12. Microfossil scheme developed by Tim Wright (unpublished report, AMEC Tunnelling and University of Brighton) for the Project Orwell Tunnel to identify the horizons in the Chalk containing flints and to guide the Tunnel Boring Machine (TBM) so that it avoided the flint bands (see also Fig. 13).

Because of the very poor exposure of the Chalk in Suffolk the engineering schemes provided the only complete picture of the possible lithologies, lateral variations, sedimentary processes, structure and weathered profiles.

Concluding remarks

Despite being poorly exposed across Suffolk, the Chalk of this region shows important features that add greatly to our understanding of its depositional development. It also presents challenges to how the Chalk of the broader East Anglia area should be classified. The region is unique in that for much of its pre-Cretaceous history it was a land area formed by the Anglo-Brabant Massif. Consequently, there is a much more direct connection between the Chalk cover and the complex underlying basement structures within this former massif; they are not separated by thick Late Palaeozoic and pre-Cretaceous Mesozoic sediments as across much of southern England. From changes in Chalk lithofacies across Suffolk it seems highly likely that these structures have had an important role in the development of the Chalk depositional environment, its resulting lithofacies, and hence also the engineering and aquifer properties of this important geological unit. Understanding these inter-relationships will undoubtedly form the basis of much future Cretaceous research within the region.

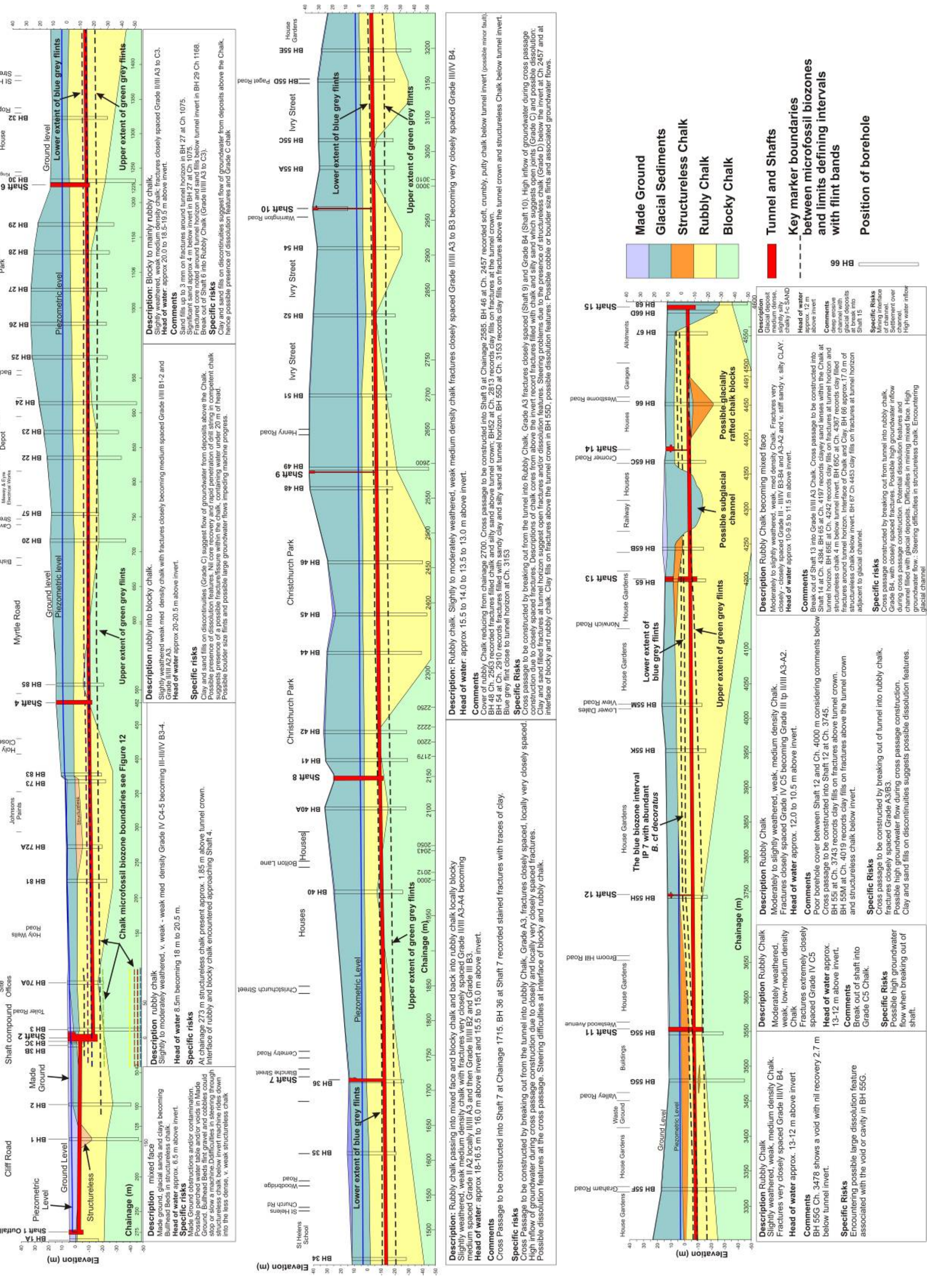

Fig. 13. Geological long sections for the Project Orwell Tunnel at Ipswich showing the geological risks in relation to the glacial sediments and degree of weathering of the Chalk. The microfossil zonation used to guide the tunnel to avoid the large blue-grey flints is also shown.

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FIGURES:

<u>Figure captions</u>

Fig. 1. Key tectonic structures affecting sedimentation of the Chalk in East Anglia, particularly Suffolk. Glinton Thrust and Basement Lineament are derived from the gravity anomaly map Fig. 9. The Midlands Microcraton margin and the Lilley Bottom Structure are derived from the BGS 1:500 000 Series Tectonic Map of Britain, Ireland, and adjacent areas, Pharaoh *et al*. (1996). SB = Sudbury–Bildeston Ridge; B St Ed = Bury St Edmunds; L = Lavenham; K = Kersey; 1, 2, 3, 4, 5, 6, boreholes shown on Fig. 1 WF = Whitham Fault; WBF = Wickham Bishops Fault; GF = Galleywood Fault; CF = Cliffe Fault; PA = Purfleet Anticline; GA = Greenwich Anticline; GF = Greenwich Fault; SF = Streatham Fault; Wim F = Wimbledon Fault.

Fig. 2. Localities and boreholes referred to in the text. Partly based on Woods *et al*. (2007).

Fig. 3A. The stratigraphy of the Chalk of Suffolk compared to the successions in the Northern and Southern provinces (not to scale). *U. anglicus* Zone not recognised in East Anglia.

Fig. 3B. Schematic geological section illustrating the main elements of the stratigraphy of the Chalk of Suffolk, the limited and non-continuous exposures (small pits and quarries) and the cored boreholes that help fill the gaps (not to scale).

Fig. 4. Correlation of borehole resistivity logs in the Chalk Group showing lateral continuity of marker beds and thinning of the lower part of the White Chalk Subgroup (Holywell and New Pit Chalk formations) in the Stowlangtoft Borehole (borehole locations shown in Fig. 1). For explanation of basis for borehole correlations see Woods (2006) and Woods & Chacksfield (in press).

Fig. 5. The Chalk succession in the Square Plantation Borehole and correlation with borehole resistivity log. Lithological log derived from interpretation of borehole video log data.

Fig. 6. The Chalk succession at Euston chalk pit [TL 89453 77359 to 89528 77481] between Bury St Edmunds and Thetford.

Fig. 7. Flint-free Blakenham Chalk Member being excavated at the Needham Market Chalk quarry, in the Gipping Valley, north-west of Ipswich. (photographer M.A. Woods; BGS image number P584984).

Fig. 8. Sections and boreholes through the Blakenham Chalk Member in the Gipping Valley and Ipswich district. Based on a figure by Woods *et al*. (2007). For location details see Figs 1 and 2.

Fig. 9. Residual Bouguer gravity anomaly map of the Suffolk region and adjoining areas, showing line of borehole correlation in Fig. 4 and position of major Caledonian thrust at depth. Red denotes positive anomalies and blue negative anomalies. Based on a figure by Woods & Chacksfield (in press). Borehole and locality details: 1 Westoe Farm, Bartlow [TL 6011 4501]; 2 Great Bradley [TL 6720 5427]; 3 Alpheton [TL 9041 5060]; 4 Stowlangtoft [TL 9475 6882]; 5 Square Plantation [TL 9560 8336]; 6 Ely-Ouse Borehole 2 [TL 7008 6976]

Fig. 10. Differences in Mundford Grades obtained from describing cores compared with those extrapolated from SPT 'N' values in Bury St Edmunds Borehole 21 (nearby Borehole 23 grades added to show consistency from core descriptions). Borehole 21 over-cored the SPT intervals to also show the influence of flint bands on SPT results (based on Mortimore *et al*., 1990). 50* indicates that the SPT was not completed by driving the rod to the full depth required. GG Marl = Grimes Graves Marl.

Fig. 11. Comparison between the Mundford, Norfolk CERN site stratigraphy compared with Borehole 23 at Bury St Edmunds Suffolk showing lateral variations in the East Anglian 'Chalk Rock' interval and nodular chalks continuing upwards in the equivalent of the Lewes Chalk in Suffolk. (Based on Mortimore *et al*., 1990)

Fig. 12. Microfossil scheme developed by Tim Wright (unpublished report, AMEC Tunnelling and University of Brighton) for the Project Orwell Tunnel to identify the horizons in the Chalk containing flints and to guide the Tunnel Boring Machine (TBM) so that it avoided the flint bands (see also Fig. 13).

Fig. 13. Geological long sections for the Project Orwell Tunnel at Ipswich showing the geological risks in relation to the glacial sediments and degree of weathering of the Chalk. The microfossil zonation used to guide the tunnel to avoid the large blue-grey flints is also shown (based broadly on Wright 2000 and AMEC Tunnelling and Anglian Water Services Ltd. Project Orwell, Ipswich drawings 97/091/1545/18 to 28, 1998)