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Geophysical log characterization of the Flamborough Chalk Formation (Late Cretaceous, Santonian – Early Campanian), East Yorkshire, UK: implications for understanding the onshore and offshore occurrence of the Late Campanian Rowe Chalk Formation

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Abstract: Whilst borehole geophysical log profiles have been matched with formational subdivisions for large parts of the Chalk Group in Lincolnshire and Yorkshire, characterization of the youngest and thickest part of the outcropping succession, represented by the marl-rich and largely flint-free Flamborough Chalk Formation, has been hindered by lack of cored and geophysically logged boreholes. In the absence of optimal primary data, a stratigraphical interpretation of geophysical logs in the Flamborough Chalk has been developed by comparison of logs from deep hydrocarbons boreholes (penetrating more than 260m of Flamborough Chalk) beneath Holderness (East Yorkshire) with generalized patterns of outcrop stratigraphy. This approach reveals geophysical log patterns that are consistent with lithology and thickness variations seen at outcrop, compatible with core and geophysical data for a deep borehole in the Flamborough Chalk at Carnaby (near Bridlington), and traceable northwards and westwards towards the margin of the Flamborough Chalk outcrop. These interpretations, and comparisons with geophysically logged offshore successions, suggest the presence of Flamborough Chalk beneath Holderness that is younger (?Late Campanian) than anything seen at outcrop, and, with the exception of possible *ex-situ* chalk rafts of glacial origin, cast doubt on the likely subsurface onshore extent of typically flint-rich Rowe Chalk Formation.

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A well-established relationship between Chalk stratigraphy and borehole geophysical logs across southern England can be traced northwards into parts of East Anglia (Murray 1986; Mortimore 1986; Mortimore & Pomerol 1987; Woods & Aldiss 2004; Woods 2006; Woods & Chacksfield 2012). Further north, lithological and stratigraphical changes mark the transition into the distinctly different Chalk of the Northern Province (sensu Mortimore 1983), covering Lincolnshire, Yorkshire and parts of north Norfolk (Wood & Smith 1978; Whitham 1991, 1993). For the Cenomanian to Coniacian parts of this succession, spanning the Ferriby, Welton and Burnham Chalk formations, the stratigraphical and marker-bed correlation of borehole geophysical logs is based on the Killingholme Borehole DG1 [TA 14981 19081] described by Barker *et al*. (1984). However, the succeeding Flamborough Chalk Formation, with an outcropping thickness approaching 200 m, dwarfing the typical thickness of the coeval Newhaven Chalk in the Southern Province (c. 60 – 70 m; Mortimore *et al*. 2001, figs 3.68-3.69) and almost equalling the combined thickness of the Ferriby, Welton and Burnham Chalk formations, has never been geophysically characterized. Mortimore (2014) hinted at the potential influence of geological structure on changes in thickness, lithology and hardness of the Northern Province Chalk, and this seems the most plausible explanation for thickening of the Flamborough Chalk. During the Mesozoic, the Flamborough Fault Zone (Fig. 1) separated the more gently subsiding East Midlands Shelf to the south, from the more rapidly subsiding Cleveland Basin to the north, and later during the Late Cretaceous – Cenozoic, became the focus of both compression and extension related to uplift of the Cleveland Basin (Kirby and Swallow 1987; Starmer 1995; Mortimore *et al*. 2001). Evidence for several intra-Late Cretaceous tectonic episodes has been recognized across Southern England (Mortimore & Pomerol 1997; Mortimore 2018). One of these (Wernigerode Phase) is broadly coincident with the onset of Flamborough Chalk deposition, and could have affected patterns of deposition across pre-existing lines of structural weakness (as possibly evidenced by significant slumping in the Flamborough Chalk at Selwicks Bay; Mortimore 2014, fig. 4.54; Fig. 1).

The Flamborough Chalk is penetrated by deep hydrocarbons boreholes and shallower water boreholes, but almost none of these have both borehole core and geophysical logs that would allow an understanding of stratigraphical relationships. An exception is the *c*. 100 m deep Carnaby Borehole [TA 1505 6486] near Bridlington (Figs 1, 4), which combines lithological, biostratigraphical and geophysical log data (Woods 1997). Biostratigraphical data allowed provisional correlation of the succession in this borehole with the middle and higher parts of the Flamborough Chalk, but at that time there was no means of confirming this by geophysical log comparisons.

In the time that has elapsed since drilling of the Carnaby Borehole in the mid-1990s, no new data have emerged to allow geophysical log correlation of the Flamborough Chalk, but it has been proposed that stratigraphically younger chalk (Late Campanian, Rowe Chalk Formation; Fig. 1), with distinctly different physical properties, extends onshore beneath Glacial/Superficial Deposits in the Holderness area (Sumbler 1996; Hopson 2005; Mortimore 2014). With the growing desire to create 3D geological models of specific regions or intervals of strategically important stratigraphy (e.g. aquifers, resource-rich units, units with critically important engineering properties; Woods *et al*. 2016), it is now pressing to fully exploit geophysical log data in the Flamborough Chalk, and to understand the subsurface geometry of younger units. To answer this need, existing geophysical log data for deep hydrocarbons boreholes has been reinvestigated, and related to broad patterns of stratigraphical variation documented in published lithological logs of outcrops proving the Flamborough Chalk. The robustness of these interpretations has been tested by examining the lateral persistence of geophysical log features, consistency with regional thickness patterns, and consistency with raw stratigraphical data (including macrofossil biostratigraphy) for the Carnaby Borehole.

Hydrocarbons borehole correlation in the Chalk beneath Holderness

Data have been released for deep hydrocarbons boreholes drilled along the east Yorkshire coast at Hornsea [TA 18460 50620] and Atwick [TA 17630 51410; TA 18350 51710] in Holderness, and at

Barmston [TA 15455 60622] south of Bridlington (Figs 1, 3 – 5). Across this area, regional structural and outcrop data suggest extensive subsurface development of Flamborough Chalk. Further south-west at Killingholme and Ella Crossroads [TA 00480 30240], where Flamborough Chalk is absent, geophysical data from hydrogeology and site investigation boreholes allow interpretation of the Ferriby, Welton and basal Burnham Chalk formations (Fig. 2). Here, borehole data support wider field evidence (Whitham 1991, 1993; Gaunt *et al*. 1992) for remarkable continuity in the pre-Flamborough Chalk succession with locations much further north at the margin of the Yorkshire Wolds (e.g. Rudston Borehole; Figs 1, 2), continuity that can help test the robustness of geophysical log interpretations of the basal Flamborough Chalk. The Black Band and North Ormsby Marl (Figs 1, 2) form well-defined markers for interpretation of the basal Welton and near-basal Burnham Chalk formations, respectively. The Black Band is an organic-rich unit formed during a protracted period of marine anoxia (Schlanger *et al*. 1987), and is typically manifest as a sharply defined, high gamma log peak. The North Ormsby Marl, locally 110 mm thick, is a volcanogenic clay unit (Wray & Wood 1998) with a high gamma log response emphasized by the very low gamma log values associated with super- and subjacent thick semi-tabular flints (Fig. 2). The appearance of these closely spaced flints is a feature of the basal Burnham Chalk, and their sharp low gamma log response is as valuable for geophysical log interpretation as the high response of the North Ormsby Marl that is closely associated with them. Figure 3 shows how these markers have been interpreted in the Barmston 1 Borehole beneath Holderness. The gamma logs of the Ella Crossroads Borehole and Barmston 1 Borehole show the same relative pattern of response, allowing confident interpretation of formational boundaries, but the amplitudes of the responses vary. This variation probably reflects differences in borehole logging environments, variable logging protocols (for example, logging speed), and that log acquisition in the Barmston 1 Borehole was probably optimized for units other than the Chalk.

Whilst the Burnham Chalk contains abundant flint and common marl seams, the Flamborough Chalk is virtually devoid of flint but with very common thin marl seams, ranging from a few millimetres to

50 mm thick, and admixtures of chalk and marl more than 100 mm thick (Fig. 6). These lithological contrasts ought to be matched by corresponding changes in gamma and sonic/resistivity logs, ideally at distances above the base of the Burnham Chalk that are compatible with composite stratigraphical data documented in regional overviews, such as those of Whitham (1991, 1993) and Sumbler (1996). These contrasts are revealed on the gamma and sonic logs of the Barmston 1 Borehole, and the gamma log of the Hornsea 1 Borehole (Fig. 4).

The Barmston 1 Borehole shows an increase in average gamma log values and decrease in average sonic log values at about 295 m depth. As well as the average shift in values, both logs show changes in their detailed character; neither this detailed change nor the general shift in log trend correspond with changes in borehole construction or logging procedure, and are interpreted as primary lithostratigraphical responses. The gamma log shows a much higher frequency of sharp gamma peaks above 306 m compared to the succession below. Correspondingly, the sonic log appears more highly serrated above 306 m; below there is less high frequency variability, but there are larger, broader shifts in the sonic log profile compared to the rather flat profile above 306 m. The change in the gamma log profile is consistent with the presence of Flamborough Chalk with its typical high frequency of marl seams. As well as marls, the Flamborough Chalk is also characterized by a profusion of stylolitic surfaces with thin coatings of marl that in combination probably help to produce the high serration of both the gamma and sonic logs. Large-scale shifts in sonic velocity can usually be related to changes in bed induration, but in the case of the Burnham/Flamborough Chalk boundary, it is probably the absence of flint in the Flamborough Chalk that causes the pronounced drop in average sonic velocity. The distance of this geophysical change above the interpreted base of the Burnham Chalk is *c.* 125 m. This compares favourably with a composite Burnham Chalk thickness of *c*. 135 m documented by Whitham (1991; includes an inferred exposure gap of 10 m), and a range of 85 – 140 m recorded by Sumbler (1996).

As well as identifying the base of the Flamborough Chalk, the hydrocarbons boreholes along the Yorkshire coast also appear to show features that can be related to subdivisions of the Flamborough Chalk (South Landing, Danes Dyke and Sewerby members) described by Whitham (1993). The boreholes at Hornsea and Barmston both show reductions in average gamma log values about 90 m above the inferred base of the Flamborough Chalk. This thickness approximately corresponds with the combined thickness of the South Landing and Danes Dyke members recorded by Whitham (1993). The Danes Dyke Member is characterized by very high frequency of marl seams (Whitham 1993), and it is likely that the gamma log shift 90 m above the inferred base of the Flamborough Chalk equates with the top of the Danes Dyke Member. There is no geophysical log evidence to allow differentiation of the South Landing Member at the base of the Flamborough Chalk.

Correlation with the Carnaby Borehole

The Carnaby Borehole [TA 1505 6486], *c.* 3.5 km south-west of Bridlington, was tentatively inferred on lithological and sparse macrofossil evidence to equate with the higher part of the Sewerby Member of Whitham (1993) (Woods 1997). The lower part of the cored borehole contains locally abundant specimens of the oyster *Pseudoperna boucheroni* (Woods 1912 non Coquand 1859), and the higher part of the borehole contains possible records of the ammonite *Scaphites* (*Discoscaphites*) *binodosus* (Röemer 1841), a subzonal index for the higher part of the Flamborough Chalk. At about 80 m depth in the Carnaby Borehole, there is an upward change in the inoceramid bivalve fauna from a succession predominantly characterized by *Sphenoceramus pinniformis* (Willett 1871), to one characterized by *Sphenoceramus patootensiformis* (Seitz 1965). Collectively these data suggest that the base of the borehole is approximately correlative with a level at or slightly below the Flamborough Sponge Beds (although sponges are not common in the Carnaby succession), in the lower part of the Sewerby Member. The Flamborough Sponge Beds appear to mark the highest common occurrence of *P. boucheroni* recorded by Whitham (1993, figs 8, 9), and these are largely absent above 80 m depth in the Carnaby succession. In the outcropping Flambrough Chalk described by Whitham (1993), the change in inoceramid faunas occurs a short distance above the Flamborough Sponge Beds, and the record of *Scaphites* occurs in an interval of close-spaced marls (Sewerby Hall Marl, Sewerby Steps Marl, Nafferton Marls), matching a similar marl association in the higher part of the Carnaby Borehole. The data for the Carnaby borehole includes a focused resistivity log, which responds similarly to a sonic log in intervals of hard/soft chalk or marl-rich/marl-poor chalk (= elevated velocity/resistivity for hard and/or marl-poor chalk; reduced velocity or resistivity for softer and/or marl-rich chalk). These geophysical data have not hitherto been used to independently explore the correlation of the Carnaby Borehole, and in the context of the current work they provide a useful test of the assumptions used to interpret the geophysical logs of the Barmston and Hornsea borehole successions.

The sonic log response in the higher part of the Barmston 1 Borehole shows a series of well-marked embayments of alternating higher and lower sonic velocity. Part of this interval is correlated with the resistivity log of the Carnaby Borehole using three of these distinctive inflections (Fig. 4). This interpretation would independently suggest that the base of the Carnaby Borehole is *c.* 19 m above the top of the Danes Dyke Member as geophysically recognized in the Barmston 1 Borehole. Composite thicknesses from the outcropping succession show that the base of the Flamborough Sponge Beds, inferred on faunal evidence to be at or just above the base of the Carnaby Borehole, are about 25 m above the top of the Danes Dyke Member. The similarity of these values supports the faunal interpretation of the Carnaby Borehole and the methodology for geophysically interpreting the Flamborough Chalk. The sonic/resistivity log datum also produces good correlation between the gamma logs for Carnaby and Barmston 1; a series of strong gamma peaks at 85 – 93 m depth at Carnaby (matched by marl seams in borehole core) corresponds with strong peaks at 177 – 184 m at Barmston 1. Outcrop data suggests that these may represent the Daneswood Marls, which typically occur a few metres below the base of the Flamborough Sponge Beds (Whitham 1993). A general decline in gamma log values at 74 m depth at Carnaby is matched by a similar trend beginning around 165 m depth in the Barmston 1 succession.

The apparent consistency in thickness of intervals in the Flamborough Chalk is not surprising. Whilst synsedimentary effects have been documented where faults intersect the coastal succession around Flamborough Head (Mortimore 2014, fig. 4.54), geophysical log correlations of, for example, the Welton Chalk between the Hull area and the margin of the Yorkshire Wolds (Fig. 2), a distance of about 40 km, reveal no significant thickness variation. Consistency between the geophysically determined thickness with Whitham's (1991) composite measured thickness for the Welton Chalk is within a couple of metres. This is not only indicative of the remarkably consistent stratigraphy of the Chalk of the Northern Province, but testament to the meticulous work of Whitham (1991, 1993) in assembling an accurate composite Chalk succession from a disparate group of exposures.

Youngest Flamborough Chalk and Rowe Chalk Formation

Comparison of lithological and geophysical data for the upper part of the Carnaby Borehole suggests that the distinctive low resistivity embayments in the log profile are caused by concentrations of marl seams. The upward continuation of these geophysical features on the sonic log at Barmston might similarly be explained. The lowest of these features on the Barmston 1 log is around 130 m depth, which using the inferred geophysical interpretation for Barmston is *c.* 165 m above the base of the Flamborough Chalk, approximately coincident with the horizon of the Sewerby Hall / Sewerby Steps Marl on Whitham's (1993) composite thickness log. This geophysical log feature occurs at 40 m depth in the Carnaby succession, and its inferred interpretation agrees with the suggested marl seam correlation independently derived from lithological and biostratigrahical data (see above).

The highest 40 m of Flamborough Chalk Formation recorded by Whitham (1993) contains groups of closely spaced marl seams; features that are broadly consistent with the cyclicity of the sonic log for the Barmston 1 succession. The intervals of low sonic velocity are matched by peaks in the gamma log, suggesting that most if not all of the sonic log cyclicity is caused by clusters of marl seams or intervals of more marly chalk. Using Whitham's (1993) composite thickness data suggests that the Nafferton Grange Upper Marls, just below the top of the outcropping Flamborough Chalk succession, occur around 95 m depth at Barmston 1. Above this, the higher succession in the Barmston 1 Borehole might be presumed to represent the upward continuation of chalk with regular clusters of marl seams, analogous to the higher part of the outcropping succession, but representing levels younger than any Flamborough Chalk seen at outcrop. The trends of progressively reducing sonic velocity and increasing gamma signal seen in the youngest chalk in the Barmston 1 Borehole are viewed with caution, as they might wholly or in part result from post-Cretaceous weathering influences, including the effects of Quaternary glaciation.

Near Hornsea, Whitham (1993) reported the presence of Late Campanian, *B. mucronata* Zone Chalk in boreholes and in isolated rafts (of presumed glacial origin) within Quaternary deposits. Loose, flint-preserved fossils belonging to the Late Campanian or Maastrichtian were also reported from beach deposits at Barmston (Whitham 1993). Later, Sumbler (1996) suggested that flinty chalk of Late Campanian age might extend under Holderness as an arcuate subcrop beneath Quaternary deposits, and designated it Rowe Chalk following the use of this term for known offshore occurrences of flint-bearing chalk of comparable age (Lott & Knox 1994). The BGS Lexicon entry for the Rowe Chalk Formation (http://www.bgs.ac.uk/lexicon/lexicon.cfm?pub=ROWE) identifies reference boreholes as Atwick 1 [TA 17630 51410] (37 – 78 m depth) and Atwick 2 [TA 18350 51710] (12 – 41 m depth) (Fig. 5). Based on these data, illustrations of the onshore development of the Rowe Chalk beneath Holderness have been reproduced by other workers (Mortimore *et al*. 2001; Hopson 2005; Mortimore 2014).

Since the Rowe Chalk is essentially defined by a combination of its age and regular flint-bearing character, it is important to establish the extent of undoubted onshore occurrences. Whitham (1993) does not mention the presence of flint in the rafts at Holderness, only the record of Campanian fossils in plastic-textured, reworked chalk. The Campanian/Maastrichtian flint-preserved fossils from the beach at Barmston were considered by Whitham (1993) to have come from subsea outcrops or to have been derived from currently unexposed strata. Sumbler (1996) suggested that geophysical logs might be used to identify the Rowe Chalk, with flint-rich intervals represented by low gamma responses and peaks in sonic velocity. At face value, this is the signature seen in the higher part of the Barmston 1 Borehole, but the likely overlap with the Carnaby succession suggests that the distinct cyclicity in the sonic log is more likely a response to marl content rather than flint horizons (see above). The low-resolution lithological logs of both Atwick boreholes (Fig. 5) suggest that flint is localized and sporadic in these successions, with intervals of marly chalk exceeding 20 m in thickness between flint bearing horizons. The Atwick 10 Borehole [TA 18790 51650] shows a uniform annotation of chert/flint on the composite log, developed throughout the entire Chalk succession. This flint distribution seems highly unlikely in the context of the known, highly variable flint occurrence in outcrop successions (Whitham 1991, 1993). These flint distributions may in part be schematic representations, or represent caved material logged in drilling mud. Apart from deep hydrocarbons boreholes, a number of shallower boreholes intersect the upper part of the Chalk in the Holderness area, and most lack any record of flint (Fig. 5).

Considering all the borehole and 'outcrop' data together for the Holderness area, it seems unlikely that regularly flinty chalk, analogous to the Rowe Chalk, is developed. The evidence of the geophysical log correlations between the Barmston and Carnably boreholes is for the presence of chalk that is largely comparable with the Flamborough Chalk Formation at outcrop, but significantly younger, with regularly developed marl seams and, perhaps on the evidence of the Atwick 1 Borehole, sporadic flint-bearing intervals. The presence of flints in the Flamborough Chalk is not without precedent. Berridge & Pattison (1994) recorded an interval of white flints and associated marl seams in the IGS North Humberside 3 Borehole [TA 2756 1677], scattered over an interval several metres thick in the upper (Early Campanian, *Sphenoceramus lingua* Zone) part of the Flamborough Chalk.

Relationship to offshore successions

In a description and definition of Chalk stratigraphical units developed in the Southern and Central North Sea, Lott & Knox (1994) illustrated a number of gamma and sonic logs through the Chalk succession. Offshore, the lithological and chronostratigraphical equivalent of the Flamborough Chalk is the Jukes Formation, described as moderately hard, variably argillaceous and with few cherts, of Santonian to Early Campanian age, and varying in thickness between 138 and 414 m. Geophysically, it is possible to match features of the sonic logs of offshore borehole successions with the sonic log of the Barmston 1 borehole (Fig. 7). The log correlations suggest that the highest Flamborough Chalk seen in the Barmston 1 Borehole (grey highlight on Fig. 7) can be traced into offshore successions; although the trends in the logs are similar, with a distinct sonic spike at the base of each of the highlighted intervals ('2a' on Fig. 7), the cyclicity is not as pronounced as the corresponding interval in the Barmston succession. Above the Jukes Formation, Lott & Knox (1994) recognized the Rowe Formation, a *c.* 200 – 270 m thick argillaceous and chert-bearing unit of Late Campanian to Maastrichtian age. Subsequently, Mortimore *et al*. (2001) reported that the base of the Rowe Formation offshore might equate with the Campanian/Maastrichtian boundary, and more recently Mortimore (2014) illustrated offshore logs of flintless and virtually marl-free Chalk of Early – Late Campanian age (= Westermost Rough Member), up to 90 m thick, occurring beneath Quaternary strata just offshore from Holderness (Mortimore & James 2015, fig 1).

If the correlation of the sonic logs shown on Figure 7 is accepted, then the published base of the Rowe Formation in these boreholes seems highly variable. In borehole 43/8a-2 (Fig. 7), the base of the Rowe Formation appears to be within an interval of log signature that can be matched with the Jukes Formation in adjacent boreholes. The relationship of the Westermost Rough Member (Mortimore 2014) to the successions shown on Figure 7 is uncertain. One possibility is that the reducing strength of cyclicity in the grey highlighted interval of the offshore boreholes shown on Figure 7 represents a lateral transition into less marl-rich successions comparable with the

Westermost Rough Member. Lithologically, the lack of flint in the Westermost Rough Member suggests a closer lithological affinity with the Flamborough Chalk, and if a stratigraphical position below the appearance of flint in strength can be proved, then the basis for this relationship will be strengthened. The correlation shown for offshore borehole 49/05-1 (Fig. 7) also supports the idea that the more than 400 m assigned to the Jukes Formation by Lott & Knox (1994) probably includes strata that are younger than any of the exposed onshore succession, rather than representing expansion of the onshore equivalent Flamborough Chalk.

Conclusions

Combining understanding of geophysical log and outcrop correlations for the Ferriby, Welton and Burnham Chalk formations with knowledge of regional thickness patterns allows interpretation of the likely geophysical log response of the Flamborough Chalk Formation in deep hydrocarbons boreholes beneath Holderness. The probable base of the Flamborough Chalk is characterized by an upward increase in the frequency of sharply defined peaks on the gamma log, an overall reduction in sonic velocity, and development of high frequency serration of the sonic log profile. An interval of relatively higher average gamma log values in the lower part of the inferred Flamborough Chalk interval may correspond with the combined South Landing and Danes Dyke members of Whitham (1993). Above this, the gamma and sonic log responses in the Chalk at Holderness can be matched with gamma and resistivity log responses in the Flamborough Chalk of the cored Carnaby Borehole. Here, biostratigraphical data for the presence of key marl seams (Daneswood, Sewerby Steps, Sewerby Hall and Nafferton Grange Marls) support tentative thickness-based interpretations of geophysical log responses at Holderness.

The youngest Chalk in the succession below Holderness is geophysically characterized by a regular cyclicity of high and low sonic velocity. The gamma log indicates that low sonic velocity intervals correspond with one or more peaks on the gamma log, suggesting that the low sonic velocity intervals are marl-rich. Beneath Holderness, this Chalk has previously been interpreted as flint-rich

Rowe Chalk, but geophysical and lithological logs favour the presence of Flamborough Chalk, probably analogous to locally flinty Flamborough Chalk recorded in the BGS Humberside 3 Borehole near Partington, but younger than any Flamborough Chalk hitherto recorded at outcrop.

The youngest Chalk seen beneath Holderness appears to be capable of correlation into offshore successions, but with a less marked cyclicity in its geophysical log signature that may indicate lateral transition into lithologies analogous to the Westermost Rough Member of Mortimore (2014).

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FIGURE CAPTIONS

Figure 1. Borehole location map and outline stratigraphy (not to scale) of the Chalk of Lincolnshire and Yorkshire. Inferred extent of Rowe Chalk based on Sumbler (1996). Holderness is the broad low-lying coastal and adjacent inland region between the Humber estuary in the south and the Yorkshire Wolds in the north and west.

Figure 2. Correlation of Ferriby, Welton and lower Burnham Chalk formations, showing continuity of key marker-beds and formational thicknesses between the Humber and the Yorkshire Wolds. See Fig. 1 for borehole locations and line of correlation section. *: no scale available for Killingholme gamma log. Numbers in parenthesis refer to borehole locations on Fig. 1. CEN = Cenomanian; CON. = Coniacian.

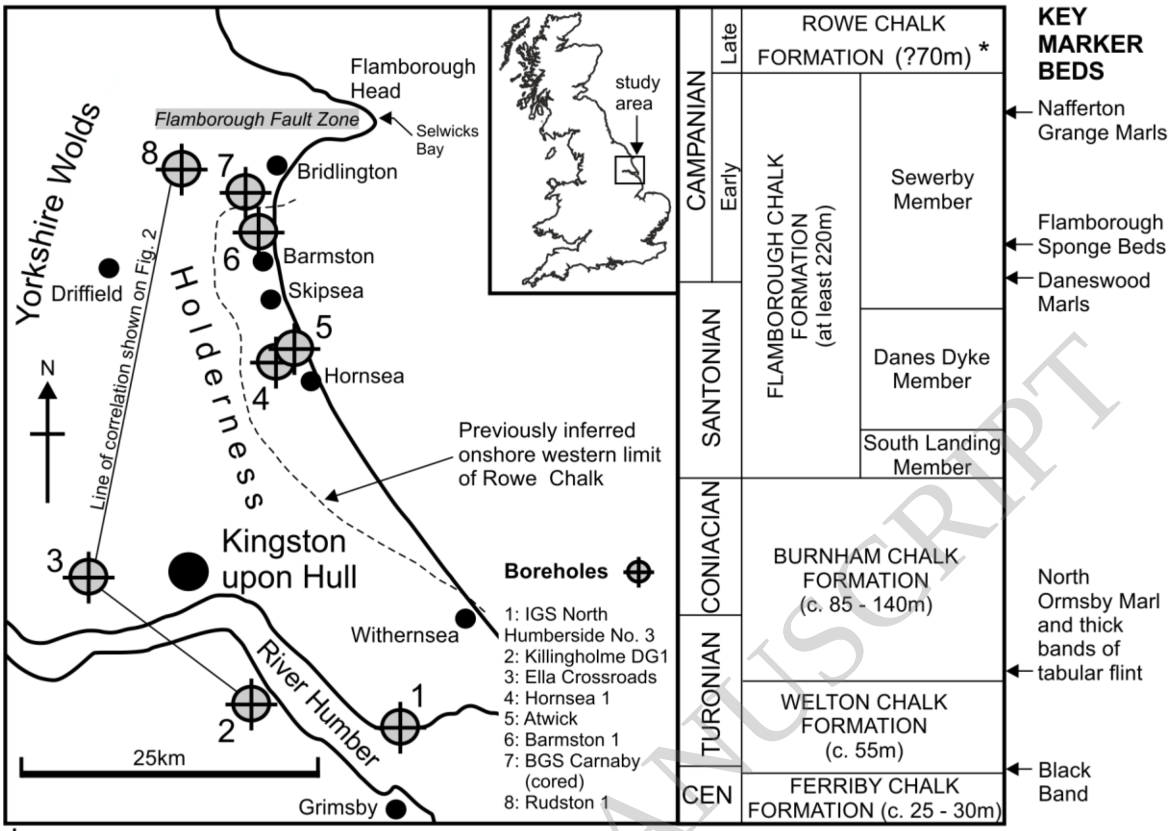
Figure 3. Geophysical log correlation and stratigraphical interpretation of the Ella Crossroads Borehole with the lower part of the Chalk Group in the Barmston 1 Borehole. Numbers in parenthesis refer to borehole locations on Fig. 1.

Figure 4. Geophysical log correlation and stratigraphical interpretation of the Barmston 1 and Hornsea 1 boreholes with the cored BGS Carnaby Borehole. 1: Interval with common specimens of the oyster *Pseudoperna boucheroni*; 2: Marl-poor interval with sponge beds and possible records of the ammonite *Scaphites* (*Discoscaphites*) *binodosus* in upper part; 3: embayments in Carnaby Borehole resistivity log corresponding with similar features in Barmston Borehole sonic log. Numbers in parenthesis refer to borehole locations on Fig. 1.

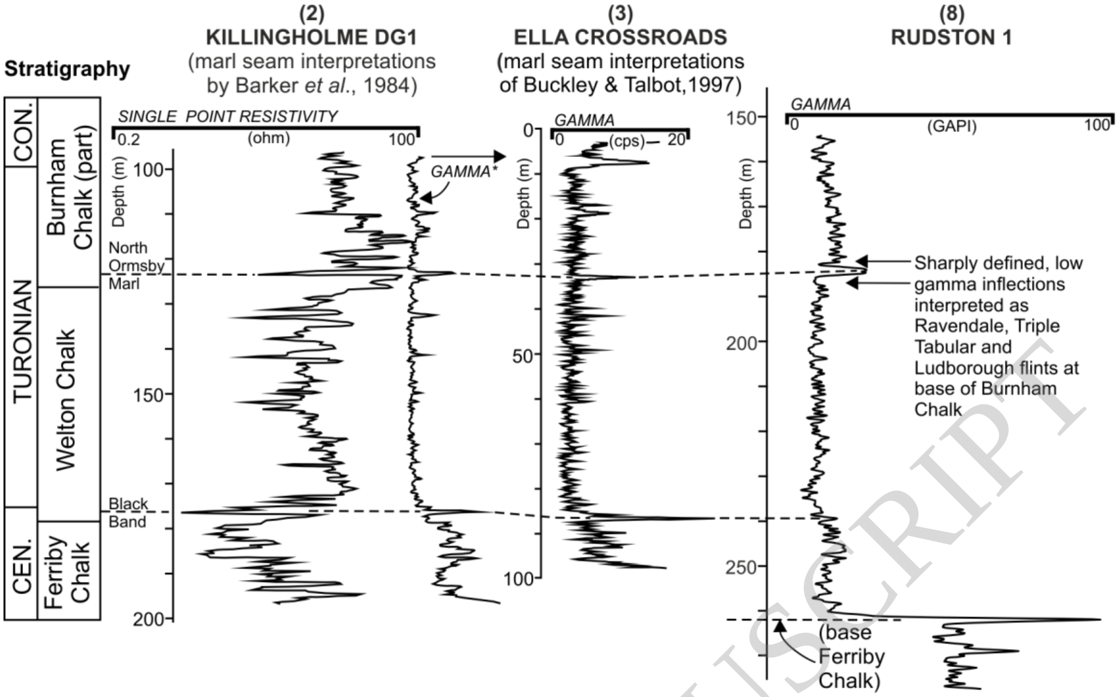
Figure 5. Lithological details of chalk proved in boreholes in the Hornsea - Skipsea area of Holderness. Deep boreholes at Atwick are reference sections for the Rowe Chalk, but their logs (transcribed from BGS archive records) suggest only sporadic occurrence of flint. Many shallow boreholes do not include any reference to flint.

Figure 6. (a) Tabular flints at the base of the Burnham Chalk Formation. (b) Flintless and marl-rich Flamborough Chalk Formation; (c) Detail of marl seam in Flamborough Chalk Formation. Photographs: M A Woods.

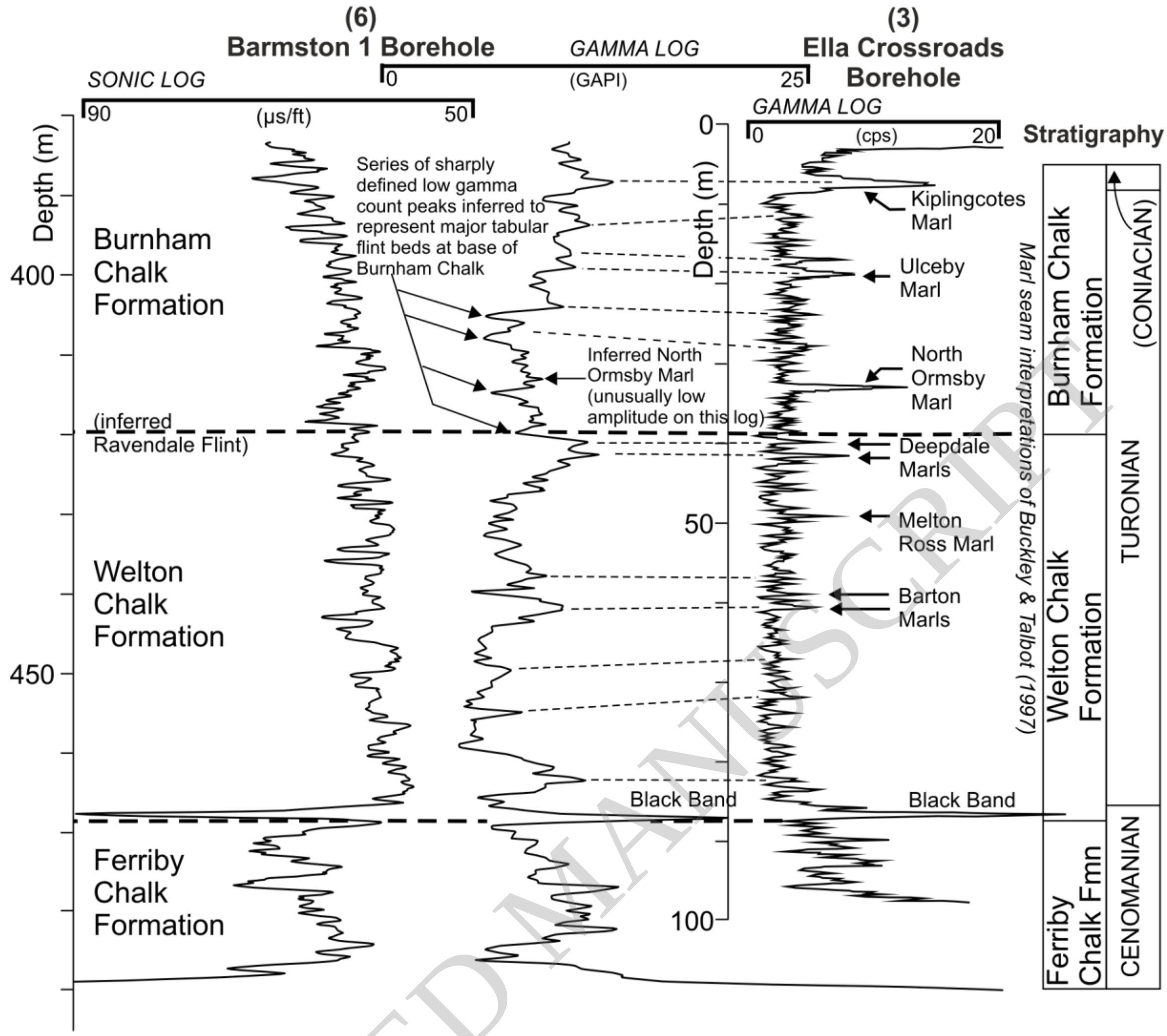
Figure 7. Correlation of the sonic log in the Chalk succession of the Barmston 1 Borehole with sonic logs for offshore boreholes 43/8a-2 and 49/05-1 described by Lott & Knox (1994). Features labelled 1, 2, 2a and 3 are laterally persistent sonic log inflection patterns used to establish correlation between the borehole successions. The bases of named stratigraphical units (Jukes Formation, Rowe Formation) in the offshore boreholes are taken from interpretations of gamma and sonic logs published by Lott & Knox (1994). Grey shading shows the likely offshore correlative of the highest chalk in the Barmston 1 Borehole.



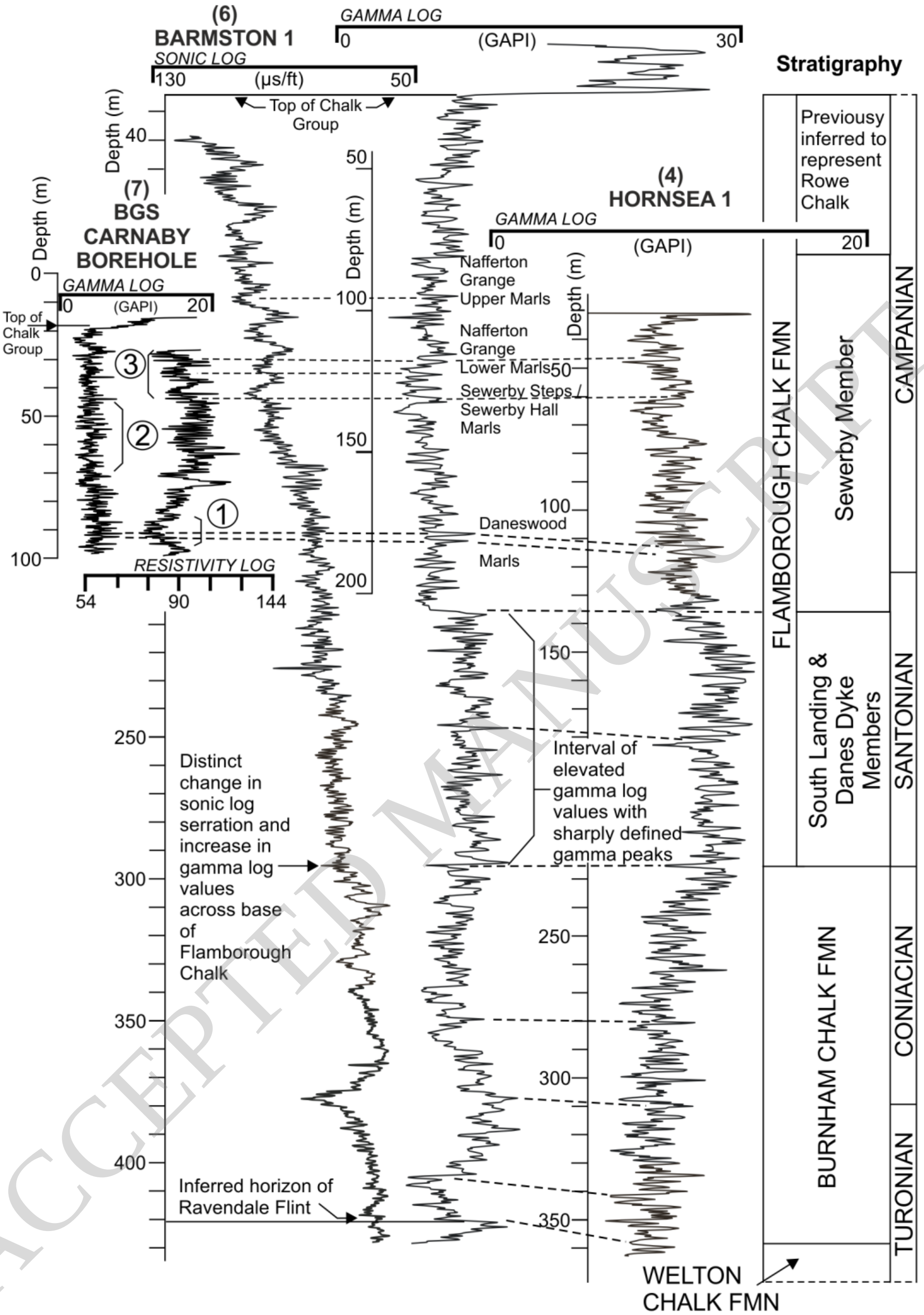
* : this work suggests that much/all of this interval as currently recognised onshore is part of Flamborough Chalk Formation

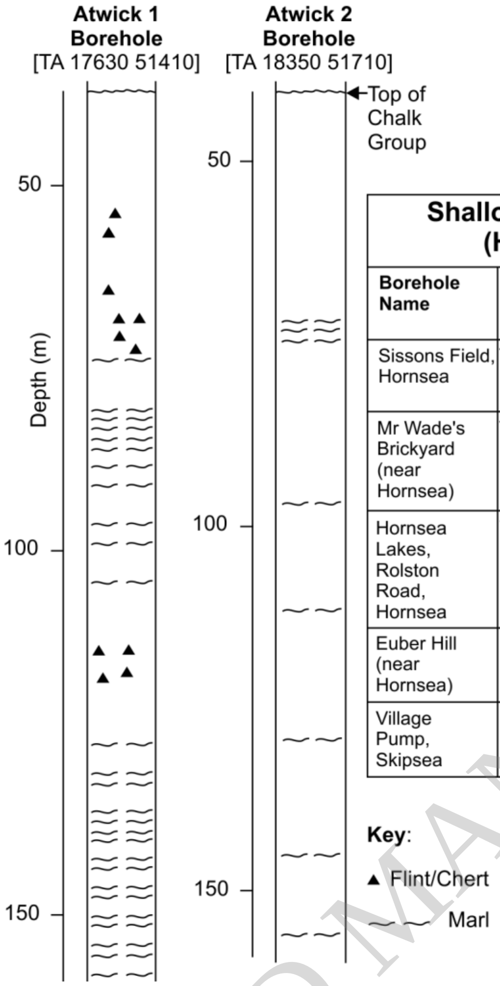


Stratigraphy
CON.
TURONIAN
CEN.
Burnham Chalk (part)
Welton Chalk
Ferriby Chalk
North Ormsby Marl
Black Band
(2)
KILLINGHOLME DG1
(marl seam interpretations by Barker et al., 1984)
SINGLE POINT RESISTIVITY
0.2
(ohm)
100
Depth (m)
100
150
200
GAMMA*
(3)
ELLA CROSSROADS
(marl seam interpretations of Buckley & Talbot,1997)
GAMMA
0
(cps)
20
Depth (m)
0
50
100
(8)
RUDSTON 1
GAMMA
0
(GAPI)
100
Depth (m)
150
200
250
Sharply defined, low gamma inflections interpreted as Ravendale, Triple Tabular and Ludborough flints at base of Burnham Chalk
(base Ferriby Chalk)



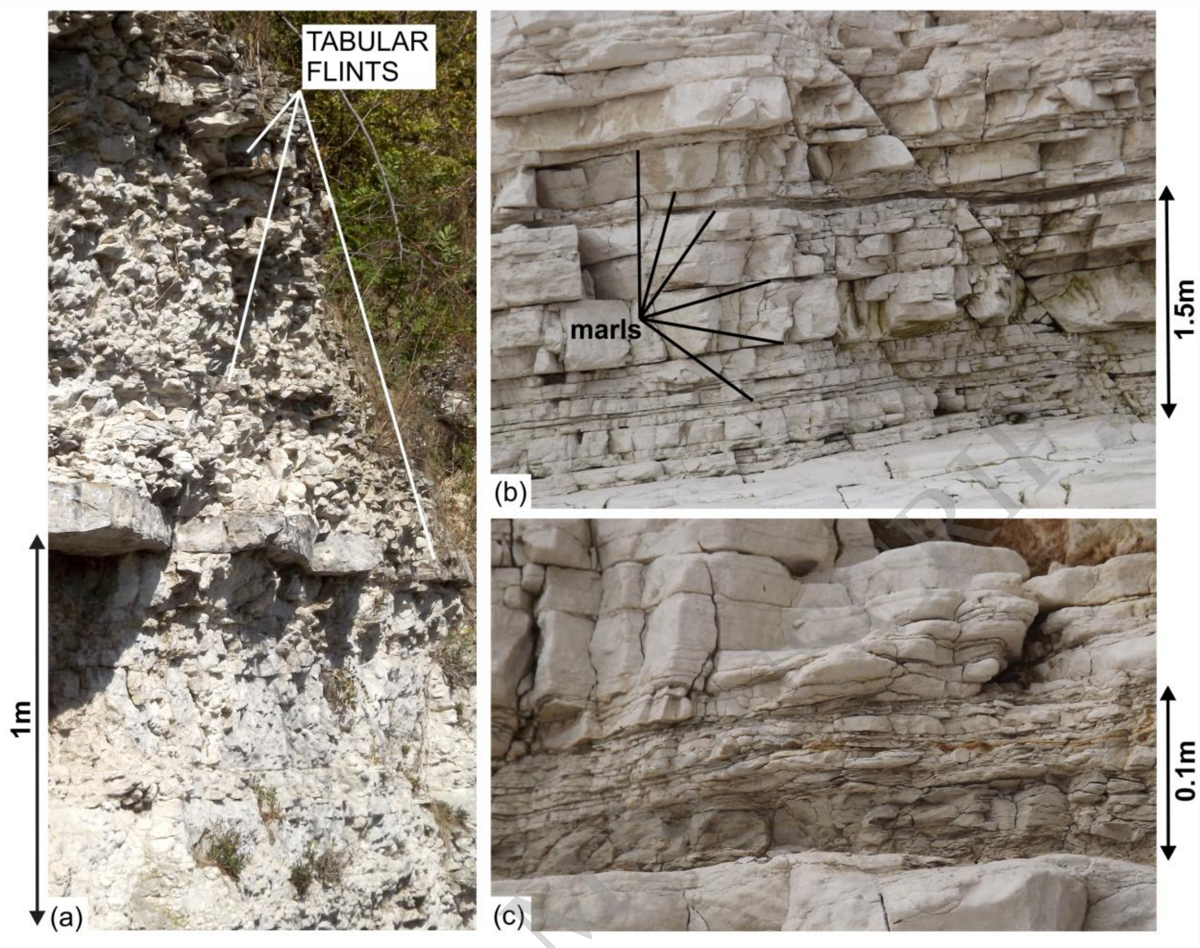
(6)
Barmston 1 Borehole
SONIC LOG
90
(µs/ft)
50
GAMMA LOG
0
(GAPI)
25
(3)
Ella Crossroads Borehole
GAMMA LOG
0
(cps)
20
Stratigraphy
Depth (m)
400
450
Depth (m)
0
50
100
Burnham Chalk Formation
Welton Chalk Formation
Ferriby Chalk Formation
Series of sharply defined low gamma count peaks inferred to represent major tabular flint beds at base of Burnham Chalk
Inferred North Ormsby Marl (unusually low amplitude on this log)
(inferred Ravendale Flint)
Black Band
Kiplingcotes Marl
Ulceby Marl
North Ormsby Marl
Deepdale Marls
Melton Ross Marl
Barton Marls
Black Band
Marl seam interpretations of Buckley & Talbot (1997)
Burnham Chalk Formation
Welton Chalk Formation
Ferriby Chalk Fmn
(CONIACIAN)
TURONIAN
CENOMANIAN

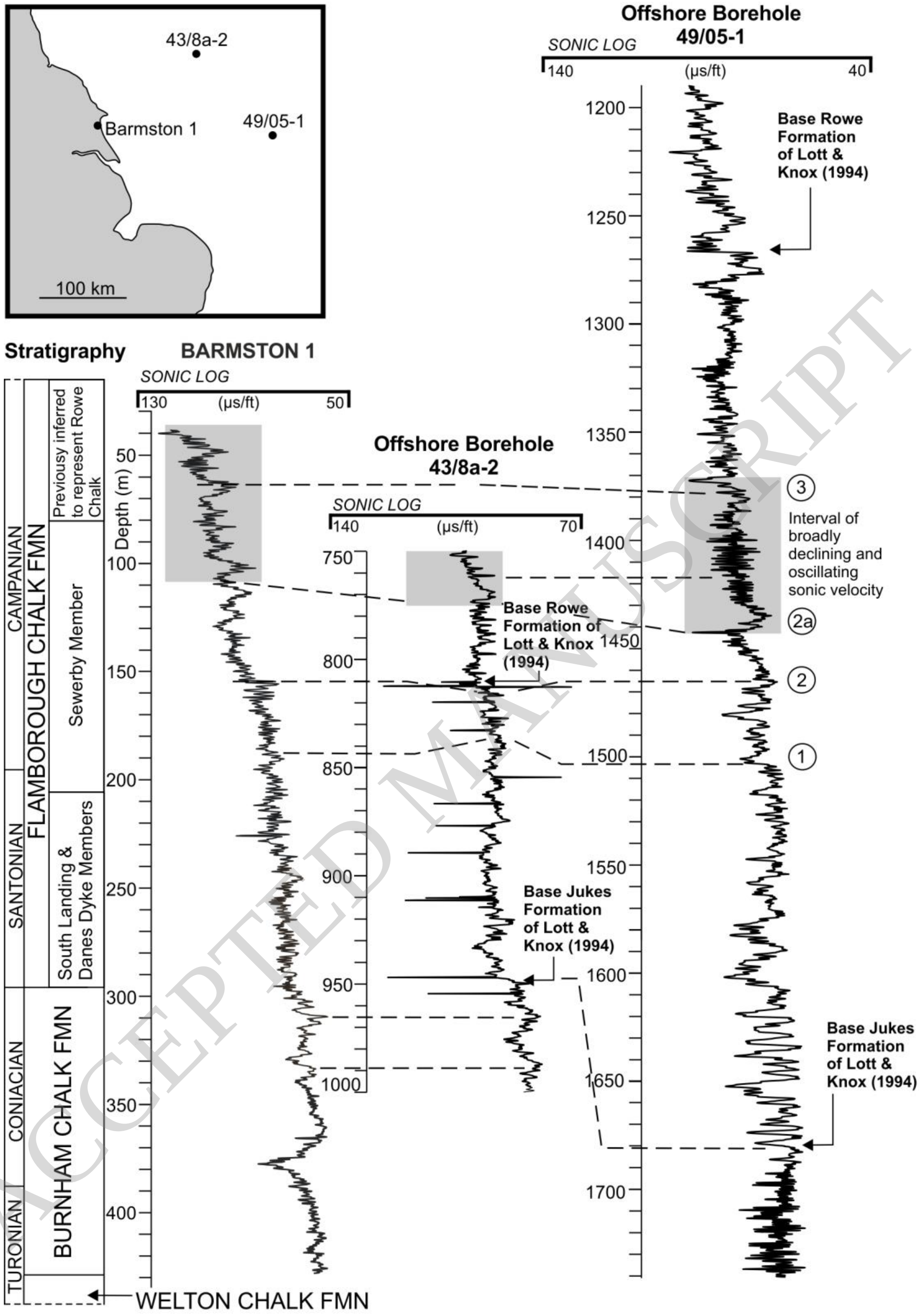

(6)
BARMSTON 1
SONIC LOG
130 (µs/ft) 50
GAMMA LOG
0 (GAPI) 30
Top of Chalk Group
Depth (m)
(7)
BGS
CARNABY
BOREHOLE
GAMMA LOG
0 (GAPI) 20
Top of Chalk Group
RESISTIVITY LOG
54 90 144
(4)
HORNSEA 1
GAMMA LOG
0 (GAPI) 20
Nafferton Grange Upper Marls
Nafferton Grange Lower Marls
Sewerby Steps / Sewerby Hall Marls
Daneswood Marls
Interval of elevated gamma log values with sharply defined gamma peaks
Distinct change in sonic log serration and increase in gamma log values across base of Flamborough Chalk
Inferred horizon of Ravendale Flint
WELTON CHALK FMN
Stratigraphy
Previousy inferred to represent Rowe Chalk
FLAMBOROUGH CHALK FMN
Sewerby Member
South Landing & Danes Dyke Members
BURNHAM CHALK FMN
CAMPANIAN
SANTONIAN
CONIACIAN
TURONIAN



Shallow Borehole Records (Holderness area)

Borehole Name	National Grid Reference	Summary of Chalk succession & thickness penetrated
Sissons Field, Hornsea	TA 19050 48790	'Soft Chalk' and 'Rubble Chalk' (10.36m)
Mr Wade's Brickyard (near Hornsea)	TA 20049 46426	Chalk with occasional bands of 'Fuller's Earth' (presumably marls) (c. 125m)
Hornsea Lakes, Rolston Road, Hornsea	TA 21266 45595	'Chalk, soft' (22m)
Euber Hill (near Hornsea)	TA 21470 44430	'Chalk, soft' (3.05m), 'Chalk, hard' (20.4m)
Village Pump, Skipsea	TA 16775 55010	'Chalk, very soft' (13.1m)


TABULAR
FLINTS
1m
(a)
marls
1.5m
(b)
0.1m
(c)


43/8a-2
Barmston 1
49/05-1
100 km
Stratigraphy
BARMSTON 1
SONIC LOG
130 (µs/ft) 50
Depth (m)
Previousy inferred to represent Rowe Chalk
Sewerby Member
South Landing & Danes Dyke Members
CAMPANIAN
SANTONIAN
CONIACIAN
TURONIAN
FLAMBOROUGH CHALK FMN
BURNHAM CHALK FMN
WELTON CHALK FMN
Offshore Borehole
43/8a-2
SONIC LOG
140 (µs/ft) 70
Base Rowe Formation of Lott & Knox (1994)
Base Jukes Formation of Lott & Knox (1994)
Offshore Borehole
49/05-1
SONIC LOG
140 (µs/ft) 40
Base Rowe Formation of Lott & Knox (1994)
Interval of broadly declining and oscillating sonic velocity
3
2a
2
1
Base Jukes Formation of Lott & Knox (1994)