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# Foraminifera of the Gault Clay Formation: An update

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## 1 Foraminifera of the Gault Clay Formation: an update

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## 9 ABSTRACT

- 10 The foraminifera of the Gault Clay Formation (Middle and Upper Albian) are
- 11 reviewed and their biostratigraphy compared to that of the standard ammonite-based
- 12 zonation and the original bed numbers that are used by most workers on the
- 13 formation. The change from an aragonitic assemblage in the Lower Gault to an
- 14 assemblage dominated by agglutinated foraminifera in the Upper Gault is discussed
- 15 in terms of changing palaeogeography and sea-level.
- 16
- 17 Keywords: Gault Clay Formation, Foraminifera, Taphonomy, Palaeoecology
- 18

## 19 **1. Introduction**

- 20 The Gault Clay Formation is a distinctive blue-grey mudstone that forms an
- 21 important component of the mid-Cretaceous succession of the United Kingdom.
- 22 Towards the South-West of England it passes laterally into the Upper Greensand
- Formation (Jukes-Browne and Hill, 1900; Drummond, 1970; Simmons et al., 1991;
- 24 Gallois and Owen, 2019 and references therein) while northwards there is a
- transition into the Red Chalk of Norfolk, Lincolnshire and Yorkshire (Burrows et al.,
- 26 1890; Gallois and Morter, 1982; Mitchell, 1995; Owen, 1995).
- In East Anglia, Gallois and Morter (1982) identified 19 beds (numbered G1– G19). These beds appeared to record small-scale rhythms (*ca.* 1–2 m thick), often with a phosphate-rich, nodular, basal bed. These rhythms are more weakly

developed in the Upper Gault Clay, as compared to the Lower Gault Clay. This
scheme was rationalized by Gallois et al. (2016) with beds G1–G19 placed within
seven distinctive sedimentary units (GE 1–7). How these two schemes relate to the
initial bed numbers of the Gault Clay Formation is shown in Gallois et al. (2016, fig. 5)
which shows how the various numbering schemes can be correlated across East
Anglia and S.E. England (Weald and Folkestone).

The Gault Clav Formation is best known for its molluscan fauna (Casev in 36 Smart et al., 1966; Morter and Wood, 1983) with ammonites providing both a viable 37 and detailed biostratigraphy (Spath, 1923–1943; Casey, 1954a, b, 1957, 1961; 38 Owen, 1958, 1963, 1971a, b, 1972, 1976, 1984). The earliest work on the Gault Clay 39 Formation concentrated on the 'type locality' of Copt Point, Folkestone, where De 40 Rance (1868), Price (1874a, b, 1876, 1879) and Jukes-Browne and Hill (1900) 41 established the lithological succession of beds, numbered I-XIII, although initially it 42 was only sub-divided into Beds I-XI: see Hart and Fox (in press) for a recent account 43 of the history of the Copt Point investigations. It was realised, in the 1970s, that there 44 were problems with the interpretation of the Copt Point succession, especially in the 45 upper levels with landslides and solifluction having 'moved' parts of the overlying 46 Glauconitic Marl and, in places, this had become confused with the glauconite-rich 47 mudstones of Bed XII. This resulted in an error that created a mistaken view of the 48 49 Bed XI - Bed XII - Bed XIII interval as well as the relationships across the Bed XIII -Glauconitic Marl boundary (Hart, 1973a, b). This confusion was resolved during 50 51 construction of the Channel Tunnel both in the 1970s and, subsequently, in the main construction phase (1988–1991): see Carter and Hart (1977), Hart (1993, 2000) and 52 53 Harris et al. (1996). This history has been described by Hart and Fox (in press, fig. 2) insofar as it impacted on the interpretation of both the hiatus at the base of the 54 Cambridge Greensand and the overall interpretation of the Copt Point succession. 55

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## 2. Foraminifera of the Gault Clay Formation

The foraminifera of the Gault Clay Formation are abundant, diverse and generally
well-preserved. Chapman's classic work on the *Foraminifera of the Gault of Folkestone*' (Chapman, 1891–1898) was based, almost exclusively, on samples from
Copt Point, using Beds I–XIII and measured distances within each unit. There is

some confusion that the nomenclature change, from using Beds I–XI to Beds I–XIII,
occurred during his work and the new additions were not sampled to the same
degree as the lower parts of the succession. It is not known how much of the earlier,
mainly European, literature was available to Chapman although this may account for
some of his variable use of taxa and other inconsistencies.

We owe our stratigraphical nomenclature to Alcide d'Orbigny and he is often 66 portrayed as the 'father of micropalaeontology' (Vénec-Peyré, 2002, 2004). His 1840 67 memoir on the Upper Cretaceous of France and adjacent countries has remained 68 one of the major contributions to the science. Reuss (1846, 1851, 1860, 1862, 1863), 69 working mainly on German material, continued the description of the abundant 70 71 foraminifera in Cretaceous assemblages. Many of the taxa used today date from the mid-19<sup>th</sup> Century, although the original illustrations of the individual foraminifera, 72 which were acceptable at the time, continue to provide problems for taxonomic work. 73 During the last 20 years of the 19<sup>th</sup> Century four major publications appeared, two of 74 which are still considered the most important works in their particular fields. 75 Chapman's (1891–1898) monograph on the foraminifera of the Gault Clay 76 77 (Formation) of Folkestone, which recorded 265 species and varieties, has remained the only comprehensive work on the British Albian. He was preceded by Berthelin 78 (1880) whose monograph on the Albian foraminifera of France described 39 new 79 80 species, most of which were later recorded by Chapman from Folkestone. The two other important contributions were the monograph on Albian foraminifera by Egger 81 (1900) and a paper on the Red Chalk of northern England by Burrows et al. (1890). 82

During the first half of the 20<sup>th</sup> Century there was a significant hiatus in 83 European research (Franke, 1925, 1928; Eichenberg, 1933a, b, 1935a, b; Brotzen, 84 1934, 1942; Marie 1938, 1941) with much of the research focusing on the higher 85 levels of the Cretaceous succession rather than the Albian. The Cushman 86 87 Laboratory for Foraminiferal Research was founded in Sharon, Massachussetts 88 (USA) by Joseph Cushman and his name appears against countless taxa that were described or re-assessed by him and his co-workers. Oil exploration was also behind 89 90 the work of Williams-Mitchell (1948) and this was the first publication on the 91 application of micropalaeontology to oil exploration on-shore U.K. In post-war Europe

there was a sudden demand for micropalaeontological expertise and a wave of new 92 work began in N. W. Europe (ten Dam, 1947, 1948a, b, 1950; Bartenstein and Brand, 93 1949, 1951; Bartenstein, 1952, 1954, 1965; Bartenstein et al., 1957, 1966; Hofker, 94 95 1954, 1957; Barnard and Banner, 1953, 1981; Barnard, 1958, 1962, 1963; Moullade, 1960, 1966: Bartenstein and Bettenstaedt, 1962; Malapris, 1965; Malapris-Bizouard, 96 97 1967, 1974; Neagu, 1965; Jannin, 1967; Magniez-Jannin, 1975, 1981, 1983; Gawor-98 Biedowa, 1972, 1982; Carter and Hart, 1977; Price, 1977). In deeper-water facies 99 and in the Tethyan Realm, while there are a number of taxa in common with N. W. European successions, the assemblages are significantly different: see, for example, 100 101 Holbourn et al. (2001) and references therein. Since the early 1980s there has been a reduction of work relating to Albian (and Cenomanian) foraminifera (but see 102 Burnhill and Ramsay, 1981; Hart et al., 1989; King et al., 1989; Freig and Kemper, 103 1989; Meyn and Vespermann, 1994; and Hart, 2000). 104

One exception to this has been the collaborative work on the Kirchrode I and 105 Il Boreholes in Germany (Fenner et al., 1996; Fenner, 2001a, b, c; Tyszka and Thies, 106 2001; Tyszka, 2006). In particular, Tyszka (2006) has presented a revised taxonomy 107 108 for the Albian Gavelinellidae, prompted by the generic revisions introduced by Revets (1996, 2001). While these suggested revisions are significant, the approach 109 adopted by Revets (a study of only holotypes, paratypes, syntypes, etc.) has 110 111 highlighted the problems of Gavelinellidae phylogeny and the authors have, for simplicity, retained the use of Berthelina and Gavelinella for many of the Albian and 112 113 Cenomanian taxa while accepting that these determinations are in need of further revision (as was begun by Tyszka, 2006). The degree of morphological variation 114 (inflation of chambers, size and form of umbilical boss, strength of peri-umbilical 115 ornament, etc.) through the succession is significant and almost none of these 116 117 variations were considered by Revets in his typological approach. Tyszka's (2006) analysis goes some way towards developing a better understanding of this variability 118 though there is still a need to look at this topic in terms of environmental and other 119 120 changes.

121 **3. Investigated successions of the Gault Clay Formation.** 

In South-East England there are numerous locations where the Gault Clay 122 123 Formation can be sampled for micropalaeontological research (Fig. 1). Extending from Copt Point, near Folkestone, the outcrop includes locations in the South Downs 124 (e.g., Eastbourne), the North Downs (e.g., Sevenoaks), the Isle of Wight (both Culver 125 Cliff and Compton Bay), and the Chilterns (e.g., Mundays Hill Quarry). Added to the 126 127 exposures on the coast and in working (or disused) guarries are the numerous boreholes (e.g., Arlesey, Glyndebourne, Mundford 'C', etc.) that have intersected the 128 129 Gault Clay Formation. This is particularly true of the area close to, and within, the site of the Channel Tunnel (see Hart, 1993, 2000; Harris et al., 1996; Hart and Fox, 130 131 in press).

## 132 3.1. Glyndebourne Borehole

This borehole was drilled in 1973 during the mapping of the Lewes District (East 133 134 Sussex) by the British Geological Survey (Lake et al., 1987). The micropalaeontology was investigated by Harris (1982) and a brief report on the 135 136 foraminifera and ostracods published by Hart and Harris (2012). A more complete assessment of the foraminifera is in preparation. The biostratigraphy of the 137 138 Glyndebourne borehole, which is mainly based on ammonites and bivalves, was included in the British Geological Survey Memoir (Lake et al., 1987) for the Lewes 139 140 District.

## 141 3.2. Mundays Hill Quarry

This guarry, located in Bedfordshire (SP 93427 27985) exposes the contact between 142 143 the Gault Clay Formation and the underlying Woburn Sands. The guarry has 144 recently been 'refreshed' and a new succession (11.40 m thick) of the Gault Clay 145 Formation became available in 2018. Historical work has divided the succession into 5 beds (numbered upwards from the contact with the underlying Woburn Sands), 146 each of which is capable of further subdivision. The ammonite biostratigraphy was 147 determined by Owen (1972), who placed the base of the Gault Clay Formation within 148 the Spathi Subzone. One of the most important 'breaks' in the succession is above 149 the Intermedius Subzone, where Owen (1972) records the absence of the Daviesi 150 151 and Nitidus subzones, creating a significant hiatus between the Niobe Subzone and

the Cristatum Zone/Subzone. Subsequent work on the Bedfordshire successionshas confirmed this hiatus (Gallois et al., 2016).

The Woburn Sands/ Gault Clay Formation boundary in Bedfordshire is highly variable and has been described by Lamplugh and Walker (1903), Lamplugh (1922), Owen (1972) and Smart (1997). Much of the debate concerns the age and nature of the Shenley Limestone, a shallow-water carbonate that is only intermittently present in the Leighton Buzzard area (Lamplugh, 1921; Eyers, 1992; Smart, 1997), though not presently seen in the Munday's Hill Quarry (Fogerty et al., 2019).

160 3.3. Copt Point (Folkestone).

The classic section at Copt Point remains a key reference, with the foraminiferal succession being described by Hart (1973b) in the Proceedings Volume of the conference on the '*Boreal Lower Cretaceous*' organised in by Raymond Casey and Peter Rawson in 1972. As explained elsewhere the error in the Bed XI/XII/XIII analysis has now been corrected (Carter and Hart, 1977; Hart et al., 1989; Hart and Fox, in press).

#### 167 3.4. Arlesey Borehole

The BGS Arlesey Borehole was drilled by the British Geological Survey in June 168 1991. It was located at TL18873463, which is only 40 m to the east of the former 169 170 Arlesey brickpit. With a total depth of 83.49 m it provided a complete succession of the Gault Clay Formation (thickness 57.35 m) as well as recording ~1.07 m of the 171 172 overlying Cambridge Greensand (Woods et al., 1995, fig. 2). The hiatus at the base of the Cambridge Greensand is clearly shown in the borehole log, as is the presence 173 174 of a layer of phosphate pebbles at the base of the Dispar Zone. Parts of the uppermost Gault Clay Formation were recorded as being noticeably un-fossiliferous 175 176 (Woods et al., 1995, pp. 274–276). Wilkinson, who studied the ostracods and foraminifera, also noted that, in places, the "impoverished microfauna for much of the 177 Upper Gault do not allow detailed biostratigraphical information" (Woods et al., 1995, 178 p. 276). It is noticeable that many of the ranges recorded in the distribution charts 179 (op. cit., figs 3, 4) are based on only a few records, with no data provided from the 180 Cambridge Greensand. The records of Globigerinelloides bentonensis, while 181

appearing to coincide with the Zone 6 'flood' of large specimens, are guite limited as 182 this taxon has a much longer total range than is indicated. The same is true of 183 species such as Citharinella pinnaeformis and Arenobulimina spp. In the samples 184 185 collected from Arlesey, Barrington and the M11 Cambridge bypass, some of which were described by Hart (1973a), the assemblages appeared to be more 'normal' with 186 187 all the diagnostic taxa present in the expected proportions and overall ranges. These data were directly comparable to, for example, the successions at Folkestone and in 188 189 the BGS Glyndebourne borehole (Hart and Harris, 2012). In the Glyndebourne succession the assemblages of foraminifera in both the Gault Clay Formation and 190 191 the transition to the overlying chalk was both diverse and abundant (Hart and Harris, 2012, figs 2, 3). This was also true of the ostracods (Hart and Harris, 2012, fig. 5) 192 where the Dispar Zone contained all the diagnostic taxa. Direct comparisons to the 193 194 Arlesey Borehole (Woods et al., 1995, fig. 3) are difficult as so few samples are 195 recorded as containing diagnostic, or indeed any, taxa. Samples from the Arlesey Borehole, inspected by MBH, partly agree with the paucity of the assemblage though 196 there are some discrepancies recorded. Zone 6a is probably not present, and that 197 agrees with both Woods et al. (1995) and other work by the authors. This is not 198 really surprising as Zone 6a has a well-known, but rather limited distribution, within 199 200 the successions of the Channel Tunnel (and parts of Surrey) and the hiatus at the 201 base of the Cambridge Greensand is clearly more significant than the comparable hiatus in the area of the Channel Tunnel. 202

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## 204 3.5. Mundford 'C' Borehole

This borehole, located in East Anglia north-west of Thetford, was studied by Sandman (1986), though the work was never formally published. The assemblages of foraminifera are comparable to those recorded from Munday's Hill Quarry (Fogerty et al., 2019) and the Cambridge bypass (Hart and Fox, in press).

209 4. Foraminiferal Zonation

The first meaningful attempt at a zonation of the Gault Clay Formation in the
twentieth century was by Carter *in* Bruckshaw (1961) in which the distribution of key

foraminifera in the Albian – Turonian interval was presented (Fig. 2). When this 212 213 preliminary zonation was published none of the taxa (listed as 1-45) were identified; 214 the figure was published without a full caption! Indeed, even in the more complete Channel Tunnel Investigation by D.J. Carter in 1964–1966, many of the taxa were 215 informally identified by number (e.g., Arenobulimina C.T.P. sp.45). Some taxa had 216 names applied but these were regarded as 'tentative' as the pressure of time to get 217 the correlation across the English Channel completed meant that taxonomic work 218 219 was not a priority. Indeed, D.J. Carter had been selected for the task as a result of his industrial micropalaeontological experience (Hart and Bailey, 2013) rather than 220 221 his research and publication record. MBH is still in possession of the original line drawings done by D.J. Carter, and the range of informal names used. In the caption 222 to Figure 2, some of the valid names have been applied, though many remain either 223 ~ 224 informal or provisional.

The zonation of the uppermost Gault Clay was confused by Hart (1973a, b), as explained in Hart and Fox (in press), but clarified in Carter and Hart (1977) after further work on borehole material recovered from the Dover/Folkestone area. This revised zonation (Fig. 3) was carried forward into the '*Stratigraphical Atlas of Fossil Foraminifera*' (Hart et al., 1989). The numbering scheme (3 – 6 for the Gault Clay), adopted by Hart (1973a, b), Carter and Hart (1977) and Hart et al. (1989), derives from the original 1961 scheme.

Zone 3 (Middle Albian): Concurrent Range Zone, *Conorboides lamplughi* and *Epistomina spinulifera*. The assemblage in this zone is somewhat limited although
those species that do occur are quite distinctive. *Conorboides lamplughi* is not found
above Zone 3, but many of the other characteristic taxa (*e.g.*, *Gavelinella tormarpensis*, *Hoeglundina chapmani*, *H. carpenteri*, *E. spinulifera* and *Arenobulimina macfadyeni*) continue into higher levels of the succession.

Zone 4 (Middle Albian): Concurrent Range Zone, *Hoeglundina carpenteri* and *Dorothia filiformis*. Within this zone *E. spinulifera* occurs in flood abundance and
specimens are often very large and highly ornamented. This was demonstrated by
Hart (1984, fig. 3) in a simple biometric analysis based on measurements of
relatively large numbers of individuals. This is particularly seen in Beds VII – IX(lower)

in the Folkestone succession close to the Middle/Upper Albian boundary. The other
taxa associated with this zone, such as *Hoeglundina carpenteri*, *H. chapmani* and *Dorothia filiformis*, continue above.

Zone 4a (Middle to Upper Albian transition): Concurrent Range Zone, 246 247 Epitomina spinulifera and Citharinella pinnaeformis. This zone can either be missing or may be very thinly developed. Its recognition depends on the dwindling numbers 248 249 of *E. spinulifera* (some of which may be reworked) and the early appearances of *Citharinella pinnaeformis.* Even though the latter species is very distinctive and 250 251 (normally) easy to identify, even in fragments, it is un-common at the beginning of its 252 range. It is unclear as to which species gives rise to C. pinnaeformis, and so an 253 evolutionary boundary to Zone 4a cannot be identified. The other taxa associated with this zone include distinctive forms such as Arenobulimina chapmani, 254 255 Nodobacularia nodulosa and Spiroloculina papyracea. The change-over from an assemblage with Arenobulimina macfadveni to one with A. chapmani is also guite 256 257 distinctive.

Zone 5 (Upper Albian): Assemblage zone of Citharinella pinnaeformis. 258 259 Although this zone is 'named' after C. pinnaeformis, this species is usually guite rare 260 and specimens often fragmentary. The remainder of the assemblage is, however, 261 quite distinctive and includes Arenobulimina chapmani (which is the dominant species), Tritaxia pyramidata, Quingueloculina antigua, Dorothia filiformis, 262 Nodobacularia nodulosa, Spiroloculina papyracea and the first occurrences of 263 Eggerellina mariae. Also making an appearance is Spiroplectinata annectens, which 264 often develops a guite distinctive growth style. With an initial triserial component, the 265 greater part of the test is biserial but can, in the later growth stages, develop a 266 uniserial pattern of slightly inflated chambers. This often gives the final specimen a 267 268 rather bizarre, but distinctive, appearance (Fogerty et al., 2019, pl. 4, figs 7-9).

Zone 5a (Upper Albian): Concurrent Range Zone of *Citharinella pinnaeformis*and *Arenobulimina sabulosa*. The appearance of the quadriserial, strongly rugose, *A. sabulosa*, together with *Marssonella ozawai* alongside *C. pinnaeformis* makes a
distinctive assemblage but it is often missing from Gault Clay successions as a result
of an hiatus at this level. Near the upper end of its range *C. pinnaeformis* also

becomes even less common than previously, and one is often reliant on the
identification of small fragments (which are, fortunately, quite characteristic). This
may be a problem for the identification of this zone though the associated species
are quite distinctive. Other associated species include *T. pyramidata*, *Berthelina intermedia* and *Arenobulimina chapmani*; the latter often being the most abundant
species present.

Zone 6 (Upper Albian): Concurrent Range Zone of *Vaginulina mediocarinata*and *Arenobulimina frankei*. *Arenobulimina sabulosa* and *A. chapmani* are normally
the dominant species, associated with *M. ozawai*. At this level *D. filiformis* and *N. nodulosa* are becoming quite rare. While planktic foraminifera are not part of this
zonation, there is a distinctive 'flood' of *Globigerinelloides bentonensis* in the middle
of Zone 6 (see Carter and Hart, 1977; Hart, 2000; Hart and Fox, 2019).

286 Zone 6a (uppermost Albian): Concurrent Range Zone of Arenobulimina sabulosa and Flourensina intermedia. This zone is characterized by a distinctive 287 288 overlap of Albian and Cenomanian taxa. Typically Albian species include A. chapmani, A. sabulosa and A. frankei, in the lower part while gradually appearing up-289 290 section are typically Cenomanian taxa such as F. intermedia, A. advena, Gaudryina 291 austiniana and Berthelina cenomanica. There are transitional forms present where 292 the differences are quite subtle but highly distinctive. This includes transitional forms between A. chapmani and A. advena, A. sabulosa and A. anglica, Berthelina 293 intermedia and B. cenomanica, most of which are parts of their respective 294 evolutionary lineages (Bailey et al., 2009). There are also early forms of Plectina 295 mariae and Berthelina baltica. As indicated by Hart and Fox (in press), Zone 6a has 296 a 'patchy' distribution and is normally cut out by the discontinuity (erosion surface) at 297 the Albian/Cenomanian boundary. It is best recorded in Channel Tunnel boreholes 298 299 off-shore Folkestone and, as a result, its position within the ammonite stratigraphy is 300 not known. In distribution it appears to be uppermost Albian and may, therefore, 301 represent a part of the Stoliczkaia dispar Zone.

The overlying Zone 7 is typically associated with a range of taxa with known Cenomanian affinities and, when present, is characterised by the Glauconitic Marl at the base of the chalk succession in South-East England (especially in the

305 Dover/Folkestone area and in Channel Tunnel boreholes). Towards the west, and 306 the north, the age of the basal glauconitic chalk becomes younger as described by

307 Carter and Hart (1977) and Hart and Fox (in press).

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## 309 **5. Distribution of Aragonitic Foraminifera**

310 One of the important groups of foraminifera recorded in the Gault Clay Formation are

the members of the Superfamily Robertinacea (Loeblich and Tappan, 1964). These

312 genera and species are now represented by the Ceratobuliminidea Cushman, 1927

following Loeblich and Tappan (1987). The Lower Cretaceous members of this

314 superfamily were described by Hart (1984), especially those recorded from the Gault

- 315 Clay Formation. The following species are recorded:
- 316 Conorboides lamplughi (SHERLOCK, 1914); Pulvinulina lamplughi SHERLOCK,
  317 1914, p. 290, pl.19, fig.16.
- 318 *Epistomina* sp. cf. *E. cretosa* TEN DAM, 1947, p. 29, fig. 6.
- 319 *Epistomina spinulifera* (REUSS, 1862); *Rotalia spinulifera* REUSS, 1862, p. 93, 320 pl.13, figs 3a-5c.
- Hoeglundina carpenteri (REUSS, 1862); Rotalia carpenteri REUSS, 1862, p. 94,
  pl.13, fig. 6a-c.
- Hoeglundina chapmani (TEN DAM, 1948); Pulvinulina caracolla (ROEMER),
  CHAPMAN, 1898, p. 7, pl.1, fig. 9.

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Epistomina cretosa is rarely described and there is a suspicion that it has probably 326 327 been included within E. spinulifera by some authors, as the two species are morphologically very similar. For example, Haig et al. (1996, fig. 7R, S) illustrate 328 329 highly ornamented forms attributed to *E. cretosa* that appear to be more closely 330 related to *E. spinulifera*. The primary difference between the two species is the 331 presence of a double keel in *E. cretosa* rather than the single, spinose keel in *E.* spinulifera. This double keel can be seen in the specimens figured by Hart (1984, pl. 332 333 2, figs 12, 16) but is not present in Haig et al.'s specimens. The Haig et al. (1996) assemblage of Albian foraminifera also includes specimens of Conorboides 334

*lamplughi* and *Epistomina chapmani* that are exceptionally close in appearance to
the N.W. European taxa. This appears to indicate that some of these aragonitic taxa
are cosmopolitan, as is much of the Albian assemblage in Western Australia.

All of these taxa are restricted (mainly) to the Lower Gault Clay and, in this 338 339 part of the succession are present in large numbers. When plots of superfamilies (sensu Loeblich and Tappan, 1964 or 1987) are constructed, there is a very 340 341 distinctive distribution of these aragonitic foraminifera within Beds I-IX (Lyelli Subzone to Orbignyi Subzone) of the Lower Gault Clay. This was noted by Hart 342 343 (1973b) and Hart and Carter (1975), as was the similarity to the superfamily distribution in the Atherfield Clay succession (Lower Aptian) of southern England 344 (Hart and Carter, 1975, text-fig. 3). The famous Atherfield Clay succession of the Isle 345 of Wight was investigated by Crittenden (1988), but he only recorded very 346 intermittent occurrences of H. chapmani in this succession below the Lower Lobster 347 Bed, with nothing like the pattern of distribution recorded by Hart and Carter (1975). 348 Crittenden also recorded *H. chapmani* in the Southern North Sea Basin, but this was 349 also in low numbers. This Middle Albian distribution of the aragonitc foraminifera 350 351 appears to occur in Kent (and parts of the Channel Tunnel which drilled into the Gault Clay Formation) as well as the eastern parts of Surrey. The more arenaceous 352 Gault Clay of the Isle of Wight does not record the same distribution, but recent work 353 354 in Bedfordshire (e.g., Munday's Hill Quarry; Fogerty et al., 2019, fig. 4) has shown 355 that the general pattern, within the mudstone facies, is present north of the Thames.

Aragonitic foraminifera are characterised by a distinctive, lustrous test and, preserved in mudstones, are often in-filled with pyrite. In parts of the Jurassic succession, only the pyritic infillings remain, the aragonitic test having been lost during taphonomy and burial. One must ask, therefore, whether the distribution of the aragonitic foraminifera in the Gault Clay Formation is a primary signal or whether it is one dominated by taphonomy?

Aragonitic foraminifera are normally associated with mudstone successions in the geological record (Makrides, 1979; Haig et al., 1996; McMillan, 2008). They are often found alongside ammonites and other molluscs that also show aragonite preservation while, in a lithology such as the chalk, aragonitic fossils are normally

absent. Mudstone successions are often aquacludes, having been compacted by 366 367 70–80% as a result of de-watering and burial. Hart et al. (2019, fig. 6) showed that sand (or silt) rich sediments do not compact to the same degree, thereby allowing 368 369 the flow of groundwater through the sediment, removing the aragonitic (and some calcitic) foraminifera. Selective preservation of aragonitic foraminifera in compacted 370 371 mudstones is, therefore, to be expected. Counts of benthic foraminifera based on 372 samples of compacted mudstones, which if reduced in thickness by 70-80%, must 373 represent large numbers of annual cycles though the ratio of aragonitic taxa to calcareous and agglutinated taxa will hopefully remain indicative of the original 374 375 assemblages.

In the Jurassic strata of the Dorset Coast, Oxford et al. (2000, 2004) showed that the fluctuations in the numbers of aragonitic and other foraminifera might represent sequences and parasequence with larger numbers of epsitominids often being associated with zones of maximum flooding. The same patterns also seem to have been preserved within the Speeton Clay Formation (Hart et al., 2009).

The 'Gault Clay Cycles' identified by Gallois and Morter (1982) may be 381 382 parasequences as they appear to be laterally persistent. The higher percentages of 383 aragonitic foraminifera in the Lower Gault Clay (and the Lower Atherfield Clay; Hart and Carter, 1975) certainly indicate that the lower parts of the Gault Clay Formation 384 and the Atherfield Clay Formation were suitable for the preservation of aragonitic 385 foraminifera. This is not the case in the Gault Clay succession of the Isle of Wight 386 387 where aragonitic foraminifera are missing and, when sieved, the mudstones have a higher sand and silt component. Whether this is a primary exclusion from a more 388 sandy/silty environment or a preservational affect is impossible to say, though it may 389 390 be significant that not even the pyrite moulds of aragonitic foraminifera are recorded 391 in these locations.

**6.** Palaeoecology and Palaeogeography

If the distribution of aragonitic foraminifera is a primary, palaeoecological signal,
what other changes in the assemblage provides supporting evidence? Agglutinated
taxa are very much more abundant after the Cristatum Zone and this is true at

Folkestone (Fig. 3), Munday's Hill Quarry (Fogerty et al., 2019, fig. 4) and in the 396 397 Glyndebourne borehole (Fig. 4). Species such as Arenobulimina, Marssonella, Tritaxia and Cribrostomoides all require clastic material with which to construct their 398 tests and the occurrence of - predominantly - silt-grade sediment is more abundant 399 above the Cristatum Zone. While one must be cautious in using planktic foraminifera, 400 401 and planktic/benthic ratios, as a guide to water depth it is clear that, especially in the smaller size fractions, planktic taxa increase in abundance up-section (above the 402 403 Cristatum Zone).

This general increase in planktic foraminifera (e.g., Muricohedbergella 404 delrioensis, M. infracretacea, M. planispira) up-section has been recorded across 405 406 South-East England, including Munday's Hill Quarry (Bedfordshire); see Fogerty et al. 407 (2019, fig. 7). With the same pattern discernable across much of South-East England, 408 this appears to be a basin-wide feature and must be linked to large scale changes in either water depth or palaeogeography. There has been little in the way of detailed 409 discussion of Albian palaeogeography since the publication of the 'Atlas of 410 Palaeogeography and Lithofacies' (Hancock and Rawson in Cope et al., 1992). The 411 only map for the interval occupied by the Gault Clay Formation is for the Upper 412 Albian (Hancock and Rawson, 1992, map K3, p. 137) which shows the 'Red Chalk' 413 to the north and the greensand facies to the south-west. The Weald Basin and 414 415 Channel Basin are in open connection to the Paris Basin (to the south) and this is 416 demonstrated by the similarity in foraminiferal assemblages in South-East England, 417 the Paris Basin and, across the Southern North Sea Basin (King et al., 1989), in the Netherlands and North Germany. 418

419 The base of the Gault Clay Formation is highly transgressive and this may well be a sequence boundary. The Lower Gault Clay and Upper Gault Clay are guite 420 421 distinctive, separated by horizons of phosphate pebbles in the Cristatum Zone. In 422 Bedfordshire the boundary is also a significant hiatus with the Nitidus and Daviesi 423 subzones missing. The more silt-rich Upper Gault Clay, with its more abundant and 424 diverse agglutinated foraminiferal assemblage and increasing numbers of planktic 425 foraminifera may represent a major flooding event (Transgressive Systems Tract, TST), which resulted in the development of a Highstand Systems Tract (HST). 426

427

#### 428 **7. Summary**

The distribution of foraminifera in the Gault Clay Formation is shown to provide a 429 viable tool for regional correlation. Many of the significant changes in the 430 431 assemblage are shown to coincide with known hiatuses in the ammonite succession and the presence of phosphate concentrations. The Lower Gault Clay, in the 432 mudstone facies, is always characterized by the presence of aragonitic foraminifera. 433 434 often showing exquisite preservation. Of particular interest is the presence of 435 comparable assemblages in the Indian Ocean (offshore South Africa) and in the 436 Carnarvon Basin of Western Australia which suggests that some of these taxa, in 437 appropriate facies, are quite cosmopolitan.

438

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445

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# 28<sup>th</sup> September 2019

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802	
803	Taxonomic notes on foraminifera discussed in the text (alphabetical order).

- As this is not a taxonomic paper, the following generic determinations largely follow
- Loeblich and Tappan (1987), even though a number of subsequent revisions (e.g.,
- 806 Revets 1996, 2001) have been proposed. As the author's names for these taxa are
- 807 part of the formal name of the fossil, they are not included in the reference list.
- 808

## 809 Benthic taxa :

- Arenobulimina advena (CUSHMAN, 1936); Hagenowella advena CUSHMAN, 1936, p.
  43, pl. 6, fig. 21a-b.
- 812 Arenobulimina anglica Cusнман, 1936, p. 27, pl. 4, fig. 8a-b.
- Arenobulimina chapmani CUSHMAN, 1936; Bulimina preslii CHAPMAN, 1892, p. 755, pl.
  12, fig. 4 (non REUSS).
- 815 Arenobulimina frankei CUSHMAN, 1936, p. 27, pl. 4, fig. 5a-b.
- 816Arenobulimina macfadyeni CUSHMAN, 1936; Bulimina orbignyi CHAPMAN, 1892, p.817754, pl.12, fig. 2 (non REUSS).
- Arenobulimina sabulosa (CHAPMAN, 1892); Bulimina preslii REUSS var. sabulosa
  CHAPMAN, 1892, p. 755, pl.12, fig. 5.
- Ataxophragmium depressa (Perner); Bulimina depressa Perner, 1892, p. 55 (p. 27),
  pl. 3, fig. 3a-b.
- 822 Berthelina baltica (BROTZEN, 1942); Gavelinella baltica BROTZEN, 1942, p. 50, pl. 1, 823 fig. 7.
- Berthelina cenomanica (BROTZEN, 1942); Cibicidoides (Cibicides) cenomanica
  BROTZEN, 1942, p. 54, pl. 2, fig. 2a–c.
- Berthelina intermedia (BERTHELIN, 1880); Anomalina intermedia BERTHELIN, 1880, p.
  67, pl. 4, fig.14a-b.
- *Citharinella pinnaeformis* (CHAPMAN, 1894); *Frondicularia pinnaeformis* CHAPMAN,
  1894, p.185, pl.3, figs 9-11.
- Conorboides lamplughi (SHERLOCK, 1914); Pulvinulina lamplughi SHERLOCK, 1914, p.
  290, pl.19, fig.16.
- Barthelin, 1880); *Gaudryina filiformis* BERTHELIN, 1880, p. 25,
  pl.1, fig. 8.

- B34 Dorothia gradata (BERTHELIN, 1880); Gaudryina gradata BERTHELIN, 1880, p. 24, pl. 1,
  fig. 6a-b.
- 836 Eggerellina mariae TEN DAM, 1950, pp.15-16, pl.1, fig.17.
- Epistomina spinulifera (REUSS, 1862); Rotalia spinulifera REUSS, 1862, p. 93, pl.13,
  figs 3a-5c.
- 839 *Flourensina intermedia* TEN DAM, 1950, p.15, pl.1, fig.16.
- 840 *Flourensina mariae* CARTER and HART, 1977, pp, 9-10, pl. 2, fig. 6.
- Gaudryina austiniana (CUSHMAN, 1936); Gaudryina (Siphogaudryina) austinana
  CUSHMAN, 1936, p. 10, pl. 2, fig. 6a–b.
- 643 Gavelinella tormarpensis BROTZEN, 1942, p. 52, pl. 1, fig. 6.
- Hoeglundina carpenteri (REUSS, 1862); Rotalia carpenteri REUSS, 1862, p. 94, pl.13,
  fig. 6a-c.
- Hoeglundina chapmani (TEN DAM, 1948); Pulvinulina caracolla (ROEMER), CHAPMAN,
  1898, p. 7, pl.1, fig. 9.
- Lingulogavelinella albiensis MALAPRIS, 1965, p. 140, pl. 4, figs 5-8, pl. 5.
- Lingulogavelinella globosa (BROTZEN); Anomalinoides globosa BROTZEN, 1945, p. 58,
   pl. 2, fig. 6a-c.
- Lingulogavelinella jarzevae (VASILENKO, 1954); Cibicides (Cibicides) jarzevae
   VASILENKO, 1954, p.121, pl.17, fig. 3a-c.
- Marssonella oxycona (REUSS, 1860); Gaudryina oxycona REUSS, 1860, p. 229, pl. 12,
   fig. 3.
- 855 Marssonella ozawai CUSHMAN, 1936, p. 43, pl. 4, fig. 10a-b.
- Nodobacularia nodulosa (CHAPMAN, 1891); Nubecularia nodulosa CHAPMAN, 1891, p.
  573, pl. 9, fig. 2.
- 858 Plectina cenomana CARTER and HART, 1977, pp. 12-13, pl. 2, fig. 9.
- Plectina mariae (FRANKE, 1928); Gaudryina ruthenica REUSS var. mariae FRANKE,
  1928, p. 146, pl. 13, fig. 15a–b.
- Pseudotextulariella cretosa (CUSHMAN, 1932); *Textulariella cretosa* CUSHMAN, 1932,
  p.97, pl.11, figs 17-19.
- Quinqueloculina antiqa (FRANKE, 1928); Miliolina venusta KARRER; CHAPMAN, 1891,
  p. 9, pl. 9, figs 5, 6.

- 865 Sagrina asperula Chapman, 1896, p. 115, pl. XII, fig. 1.
- 866 Spiroloculina papyracea BURROWS, SHERBORN & BAILEY, 1890, p. 551, pl. 8, fig. 1.
- Spiroplectinata annectens (PARKER & JONES, 1863); *Textularia annectens* PARKER &
  JONES, 1863, p. 92, text.fig. 1.
- 869 Tritaxia macfadyeni Cushman, 1936, p. 3, pl. 1, fig. 6a-b.
- 870 *Tritaxia pyramidata* REUSS, 1862, pp. 32, 88, pl.1, fig. 8a-c.
- Vaginulina mediocarinata TEN DAM, 1950, pp. 36–37, pl. 3, fig. 3.
- 872

## 873 Planktic Taxa:

- Dicarinella hagni (SCHEIBNEROVA); Praeglobotruncana hagni SCHEIBNEROVA, 1962,
   pp. 219, 225-226, text-fig. 6a-c.
- 876 *Dicarinella imbricata* (Mornod); Globotruncana imbricata Mornod, 1949, p. 589, text-877 fig. 5, Illa-d.
- Favusella washitensis (CARSEY, 1926); Globigerina washitensis CARSEY, 1926, p. 44,
  pl. 7, fig.10, pl. 8, fig. 2.
- B80 Globigerinelloides bentonensis (MORROW, 1934); Anomalina bentonensis MORROW,
  1934, p. 201, pl. 30, fig. 4a-b.
- 882 *Guembilitria harrisi* TAPPAN, 1940, p. 115, pl. 19, fig. 2a-b.
- Helvetoglobotruncana helvetica (BOLLI); Globotruncana helvetica BOLLI, p. 226, pl. 9,
  figs 6-8, text-fig. 1 (9-12).
- 885 Heterohelix globulosa (Ehrenberg); Textularia globulosa Ehrenberg, 1840,
- Heterohelix moremani (CUSHMAN, 1938); Guembelina moremani CUSHMAN, 1938, p.
  10, pl. 2, figs 1-3.
- Marginotruncana pseudolinneiana Pessagno, 1967, p. 310, pl. 65, figs 24-27, pl. 76,
   figs 1-3, 24-27.
- Muricohedbergella delrioensis (CARSEY); Globigerina cretacea D'ORBIGNY var.
   delrioensis CARSEY, 1926, p. 43.
- Muricohedbergella infracretacea (GLAESSNER); Globigerina infracretacea GLAESSNER,
  1937, p. 28, text-fig. 1.

- Muricohedbergella planispira (TAPPAN); Globigerina planispira TAPPAN, 1940, p. 12,
  pl. 19, fig. 12.
- 896 Praeglobotruncana delrioensis (PLUMMER); Globrotalia delrioensis PLUMMER, 1931, p.
  897 199, pl. 13, fig. 2a-c.
- Rotalipora cushmani (MORROW); Globorotalia cushmani MORROW,1934, p. 199, pl. 31,
  figs 2, 4.
- Thalmanninella globotruncanoides (Sigal); Rotalipora globotruncanoides Sigal, 1948,
   p. 100, pl. 1, fig. 4, pl. 2, figs 3-5.
- Thalmanninella greenhornensis (MORROW); Globorotalia greenhornensis MORROW,
  1934, p. 199, pl. 39, fig. 1.
- Thalmanninella reicheli (Mornod); Globotruncana (Rotalipora) reicheli Mornod, 1949,
   p. 583, text-fig. 5, IVa-c.
- 906

## 907 Figure Captions:

Figure 1. Outline geological map of South-East England showing the localitiesmentioned or discussed in the text.

910 Figure 2. Original zonation of the mid-Cretaceous of Southern England using

911 foraminifera (Carter *in* Bruckshaw et al., 1961) reproduced with the permission

- of the Institution of Civil Engineers. Zones 3–6 represent the Gault Clay
- 913 Formation. Some key taxa are identified with both the original names (applied
- by D.J. Carter), updated where possible, but others remain indeterminate. (1)
- 915 Marginotruncana pseudolinneiana; (2) Helvetoglobotruncana helvetica; (3)
- 916 Dicarinella imbricata; (4) Heterohelix globulosa; (8) Dicarinella hagni; (10)
- 917 Lingulogavelinella globosa (Biorostella sp., C.T.P.); (12) Tritaxia pyramidata
- 918 and T. macfadyeni; (13) Spiroplectinata annectens; (14) Flourensina mariae
- 919 (Flourensina crenata C.T.P.); (15) Rotalipora cushmani; (16) Pleurostomella sp.
- 920 26 C.T.P.; (17) Plectina cenomana; (18) Plectina mariae; (19) Pernerina sp.
- 921 C.T.P., now Arenobulimina depressa; (20) Spiroloculina papyracea; (21)
- 922 Thalmanninella reicheli and T. greenhornensis; (22) Praeglobotruncana sp. cf.
- 923 P. delrioensis; (23) Thalmanninella globotruncanoides; (24) Arenobulimina
- 924 advena; (25) spicules of hexactinellid sponges; (26) Flourensina intermedia; (27)

- 925 Marssonella ozawai; (28) Quinqueloculina antiqua; (29) Dorothia filiformis; (30)
- 926 Muricohedbergella spp.; (31) Nodobacularia nodulosa; (32) Arenobulimina
- 927 chapmani; (33) Dentalina sp. 38 C.T.P.; (35) Epistomina spinulifera; (37)
- 928 Sagrina asperula; (38) Conorboides lamplughi; (39) Citharinella pinnaeformis;
- 929 (40) Ammobaculoides sp. C.T.P.; (43) Hoeglundina chapmani; (44)
- 930 Hoeglundina carpenteri.
- Figure 3. Copt Point succession of the Gault Clay Formation showing the lithology,
  ammonite zonation, foraminiferal zonation and the distribution of the various
  superfamilies (*sensu* Loeblich and Tappan, 1964).
- 934 Figure 4. Distribution of stratigraphically significant foraminifera in the Glyndebourne
- Borehole (based on Hart and Harris, 2012). It is interesting to note that the
- 936 range of Favusella washitensis appears much longer than in the Copt Point
- 937 succession and this is reflected in the expanded Zone 4/5 transitional interval
- 938 picked out by the benthic foraminifera.