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

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8

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
23 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
25 transition into the Red Chalk of Norfolk, Lincolnshire and Yorkshire (Burrows et al.,
26 1890; Gallois and Morter, 1982; Mitchell, 1995; Owen, 1995).

27 In East Anglia, Gallois and Morter (1982) identified 19 beds (numbered G1–
28 G19). These beds appeared to record small-scale rhythms (ca. 1–2 m thick), often
29 with a phosphate-rich, nodular, basal bed. These rhythms are more weakly

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

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

56 **2. Foraminifera of the Gault Clay Formation**

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

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

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

83 During the first half of the 20th Century there was a significant hiatus in
84 European research (Franke, 1925, 1928; Eichenberg, 1933a, b, 1935a, b; Brotzen,
85 1934, 1942; Marie 1938, 1941) with much of the research focusing on the higher
86 levels of the Cretaceous succession rather than the Albian. The Cushman
87 Laboratory for Foraminiferal Research was founded in Sharon, Massachusetts
88 (USA) by Joseph Cushman and his name appears against countless taxa that were
89 described or re-assessed by him and his co-workers. Oil exploration was also behind
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

92 there was a sudden demand for micropalaeontological expertise and a wave of new
93 work began in N. W. Europe (ten Dam, 1947, 1948a, b, 1950; Bartenstein and Brand,
94 1949, 1951; Bartenstein, 1952, 1954, 1965; Bartenstein *et al.*, 1957, 1966; Hofker,
95 1954, 1957; Barnard and Banner, 1953, 1981; Barnard, 1958, 1962, 1963; Moullade,
96 1960, 1966; Bartenstein and Bettenstaedt, 1962; Malapris, 1965; Malapris-Bizouard,
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.
100 European successions, the assemblages are significantly different: see, for example,
101 Holbourn *et al.* (2001) and references therein. Since the early 1980s there has been
102 a reduction of work relating to Albian (and Cenomanian) foraminifera (but see
103 Burnhill and Ramsay, 1981; Hart *et al.*, 1989; King *et al.*, 1989; Freig and Kemper,
104 1989; Meyn and Vespermann, 1994; and Hart, 2000).

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

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

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

132 3.1. *Glyndebourne Borehole*

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

141 3.2. *Munday's Hill Quarry*

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

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

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

160 3.3. *Copt Point (Folkestone)*.

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

167 3.4. *Arlesey Borehole*

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

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

203

204 3.5. Mundford 'C' Borehole

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

209 4. Foraminiferal Zonation

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

212 foraminifera in the Albian – Turonian interval was presented (Fig. 2). When this
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
215 Channel Tunnel Investigation by D.J. Carter in 1964–1966, many of the taxa were
216 informally identified by number (e.g., *Arenobulimina* C.T.P. sp.45). Some taxa had
217 names applied but these were regarded as ‘tentative’ as the pressure of time to get
218 the correlation across the English Channel completed meant that taxonomic work
219 was not a priority. Indeed, D.J. Carter had been selected for the task as a result of
220 his industrial micropalaeontological experience (Hart and Bailey, 2013) rather than
221 his research and publication record. MBH is still in possession of the original line
222 drawings done by D.J. Carter, and the range of informal names used. In the caption
223 to Figure 2, some of the valid names have been applied, though many remain either
224 informal or provisional.

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

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

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

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

246 Zone 4a (Middle to Upper Albian transition): Concurrent Range Zone,
247 *Epitomina spinulifera* and *Citharinella pinnaeformis*. This zone can either be missing
248 or may be very thinly developed. Its recognition depends on the dwindling numbers
249 of *E. spinulifera* (some of which may be reworked) and the early appearances of
250 *Citharinella pinnaeformis*. Even though the latter species is very distinctive and
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
254 with this zone include distinctive forms such as *Arenobulimina chapmani*,
255 *Nodobacularia nodulosa* and *Spiroloculina papyracea*. The change-over from an
256 assemblage with *Arenobulimina macfadyeni* to one with *A. chapmani* is also quite
257 distinctive.

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

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

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

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

286 Zone 6a (uppermost Albian): Concurrent Range Zone of *Arenobulimina*
287 *sabulosa* and *Flourensina intermedia*. This zone is characterized by a distinctive
288 overlap of Albian and Cenomanian taxa. Typically Albian species include *A.*
289 *chapmani*, *A. sabulosa* and *A. frankei*, in the lower part while gradually appearing up-
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
293 between *A. chapmani* and *A. advena*, *A. sabulosa* and *A. anglica*, *Berthelina*
294 *intermedia* and *B. cenomanica*, most of which are parts of their respective
295 evolutionary lineages (Bailey et al., 2009). There are also early forms of *Plectina*
296 *mariae* and *Berthelina baltica*. As indicated by Hart and Fox (in press), Zone 6a has
297 a ‘patchy’ distribution and is normally cut out by the discontinuity (erosion surface) at
298 the Albian/Cenomanian boundary. It is best recorded in Channel Tunnel boreholes
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.

302 The overlying Zone 7 is typically associated with a range of taxa with known
303 Cenomanian affinities and, when present, is characterised by the Glauconitic Marl at
304 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).

308

309 **5. Distribution of Aragonitic Foraminifera**

310 One of the important groups of foraminifera recorded in the Gault Clay Formation are
311 the members of the Superfamily Robertinacea (Loeblich and Tappan, 1964). These
312 genera and species are now represented by the Ceratobuliminidea Cushman, 1927
313 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.

321 *Hoeglundina carpenteri* (REUSS, 1862); *Rotalia carpenteri* REUSS, 1862, p. 94,
322 pl.13, fig. 6a-c.

323 *Hoeglundina chapmani* (TEN DAM, 1948); *Pulvinulina caracolla* (ROEMER),
324 CHAPMAN, 1898, p. 7, pl.1, fig. 9.

325

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

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

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

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

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

366 absent. Mudstone successions are often aquacludes, having been compacted by
367 70–80% as a result of de-watering and burial. Hart et al. (2019, fig. 6) showed that
368 sand (or silt) rich sediments do not compact to the same degree, thereby allowing
369 the flow of groundwater through the sediment, removing the aragonitic (and some
370 calcitic) foraminifera. Selective preservation of aragonitic foraminifera in compacted
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
374 calcareous and agglutinated taxa will hopefully remain indicative of the original
375 assemblages.

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

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

392 **6. Palaeoecology and Palaeogeography**

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

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

404 This general increase in planktic foraminifera (e.g., *Muricohedbergella*
405 *delrioensis*, *M. infracretacea*, *M. planispira*) up-section has been recorded across
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
409 either water depth or palaeogeography. There has been little in the way of detailed
410 discussion of Albian palaeogeography since the publication of the '*Atlas of*
411 *Palaeogeography and Lithofacies*' (Hancock and Rawson in Cope et al., 1992). The
412 only map for the interval occupied by the Gault Clay Formation is for the Upper
413 Albian (Hancock and Rawson, 1992, map K3, p. 137) which shows the 'Red Chalk'
414 to the north and the greensand facies to the south-west. The Weald Basin and
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
418 Netherlands and North Germany.

419 The base of the Gault Clay Formation is highly transgressive and this may
420 well be a sequence boundary. The Lower Gault Clay and Upper Gault Clay are quite
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,
426 TST), which resulted in the development of a Highstand Systems Tract (HST).

427

428 **7. Summary**

429 The distribution of foraminifera in the Gault Clay Formation is shown to provide a
430 viable tool for regional correlation. Many of the significant changes in the
431 assemblage are shown to coincide with known hiatuses in the ammonite succession
432 and the presence of phosphate concentrations. The Lower Gault Clay, in the
433 mudstone facies, is always characterized by the presence of aragonitic foraminifera,
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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799 Formation (Middle & Upper Albian) in the BGS Arlesey Borehole, Bedfordshire.
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- 801
- 802
- 803 **Taxonomic notes on foraminifera discussed in the text (alphabetical order).**

804 As this is not a taxonomic paper, the following generic determinations largely follow
805 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 :**

810 *Arenobulimina advena* (CUSHMAN, 1936); *Hagenowella advena* CUSHMAN, 1936, p.
811 43, pl. 6, fig. 21a-b.

812 *Arenobulimina anglica* CUSHMAN, 1936, p. 27, pl. 4, fig. 8a-b.

813 *Arenobulimina chapmani* CUSHMAN, 1936; *Bulimina preslii* CHAPMAN, 1892, p. 755, pl.
814 12, fig. 4 (*non* REUSS).

815 *Arenobulimina frankei* CUSHMAN, 1936, p. 27, pl. 4, fig. 5a-b.

816 *Arenobulimina macfadyeni* CUSHMAN, 1936; *Bulimina orbigny* CHAPMAN, 1892, p.
817 754, pl.12, fig. 2 (*non* REUSS).

818 *Arenobulimina sabulosa* (CHAPMAN, 1892); *Bulimina preslii* REUSS var. *sabulosa*
819 CHAPMAN, 1892, p. 755, pl.12, fig. 5.

820 *Ataxophragmium depressa* (Perner); *Bulimina depressa* Perner, 1892, p. 55 (p. 27),
821 pl. 3, fig. 3a-b.

822 *Berthelina baltica* (BROTZEN, 1942); *Gavelinella baltica* BROTZEN, 1942, p. 50, pl. 1,
823 fig. 7.

824 *Berthelina cenomanica* (BROTZEN, 1942); *Cibicidoides (Cibicides) cenomanica*
825 BROTZEN, 1942, p. 54, pl. 2, fig. 2a–c.

826 *Berthelina intermedia* (BERTHELIN, 1880); *Anomalina intermedia* BERTHELIN, 1880, p.
827 67, pl. 4, fig.14a-b.

828 *Citharinella pinnaeformis* (CHAPMAN, 1894); *Frondicularia pinnaeformis* CHAPMAN,
829 1894, p.185, pl.3, figs 9-11.

830 *Conorboides lamplughi* (SHERLOCK, 1914); *Pulvinulina lamplughi* SHERLOCK, 1914, p.
831 290, pl.19, fig.16.

832 *Dorothyia filiformis* (BERTHELIN, 1880); *Gaudryina filiformis* BERTHELIN, 1880, p. 25,
833 pl.1, fig. 8.

- 834 *Dorothia gradata* (BERTHELIN, 1880); *Gaudryina gradata* BERTHELIN, 1880, p. 24, pl. 1,
835 fig. 6a-b.
- 836 *Eggerellina mariae* TEN DAM, 1950, pp.15-16, pl.1, fig.17.
- 837 *Epistomina spinulifera* (REUSS, 1862); *Rotalia spinulifera* REUSS, 1862, p. 93, pl.13,
838 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.
- 841 *Gaudryina austiniana* (CUSHMAN, 1936); *Gaudryina (Siphogaudryina) austiniana*
842 CUSHMAN, 1936, p. 10, pl. 2, fig. 6a–b.
- 843 *Gavelinella tormarpensis* BROTZEN, 1942, p. 52, pl. 1, fig. 6.
- 844 *Hoeglundina carpenteri* (REUSS, 1862); *Rotalia carpenteri* REUSS, 1862, p. 94, pl.13,
845 fig. 6a-c.
- 846 *Hoeglundina chapmani* (TEN DAM, 1948); *Pulvinulina caracolla* (ROEMER), CHAPMAN,
847 1898, p. 7, pl.1, fig. 9.
- 848 *Lingulogavelinella albiensis* MALAPRIS, 1965, p. 140, pl. 4, figs 5-8, pl. 5.
- 849 *Lingulogavelinella globosa* (BROTZEN); *Anomalinoides globosa* BROTZEN, 1945, p. 58,
850 pl. 2, fig. 6a-c.
- 851 *Lingulogavelinella jarzevae* (VASILENKO, 1954); *Cibicides (Cibicides) jarzevae*
852 VASILENKO, 1954, p.121, pl.17, fig. 3a-c.
- 853 *Marssonella oxycona* (REUSS, 1860); *Gaudryina oxycona* REUSS, 1860, p. 229, pl. 12,
854 fig. 3.
- 855 *Marssonella ozawai* CUSHMAN, 1936, p. 43, pl. 4, fig. 10a-b.
- 856 *Nodobacularia nodulosa* (CHAPMAN, 1891); *Nubecularia nodulosa* CHAPMAN, 1891, p.
857 573, pl. 9, fig. 2.
- 858 *Plectina cenomana* CARTER and HART, 1977, pp. 12-13, pl. 2, fig. 9.
- 859 *Plectina mariae* (FRANKE, 1928); *Gaudryina ruthenica* REUSS var. *mariae* FRANKE,
860 1928, p. 146, pl. 13, fig. 15a–b.
- 861 *Pseudotextulariella cretosa* (CUSHMAN, 1932); *Textulariella cretosa* CUSHMAN, 1932,
862 p.97, pl.11, figs 17-19.
- 863 *Quinqueloculina antiqa* (FRANKE, 1928); *Miliolina venusta* KARRER; CHAPMAN, 1891,
864 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.
- 867 *Spiroplectinata annectens* (PARKER & JONES, 1863); *Textularia annectens* PARKER &
868 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.
- 871 *Vaginulina mediocarinata* TEN DAM, 1950, pp. 36–37, pl. 3, fig. 3.
- 872
- 873 **Planktic Taxa:**
- 874 *Dicarinella hagni* (SCHEIBNEROVA); *Praeglobotruncana hagni* SCHEIBNEROVA, 1962,
875 pp. 219, 225-226, text-fig. 6a-c.
- 876 *Dicarinella imbricata* (Mornod); *Globotruncana imbricata* Mornod, 1949, p. 589, text-
877 fig. 5, Illa-d.
- 878 *Favusella washitensis* (CARSEY, 1926); *Globigerina washitensis* CARSEY, 1926, p. 44,
879 pl. 7, fig.10, pl. 8, fig. 2.
- 880 *Globigerinelloides bentonensis* (MORROW, 1934); *Anomalina bentonensis* MORROW,
881 1934, p. 201, pl. 30, fig. 4a-b.
- 882 *Guembilitria harrisi* TAPPAN, 1940, p. 115, pl. 19, fig. 2a-b.
- 883 *Helvetoglobotruncana helvetica* (BOLLI); *Globotruncana helvetica* BOLLI, p. 226, pl. 9,
884 figs 6-8, text-fig. 1 (9-12).
- 885 *Heterohelix globulosa* (Ehrenberg); *Textularia globulosa* Ehrenberg, 1840,
- 886 *Heterohelix moremani* (CUSHMAN, 1938); *Guembelina moremani* CUSHMAN, 1938, p.
887 10, pl. 2, figs 1-3.
- 888 *Marginotruncana pseudolinneiana* Pessagno, 1967, p. 310, pl. 65, figs 24-27, pl. 76,
889 figs 1-3, 24-27.
- 890 *Muricohedbergella delrioensis* (CARSEY); *Globigerina cretacea* D'ORBIGNY var.
891 *delrioensis* CARSEY, 1926, p. 43.
- 892 *Muricohedbergella infracretacea* (GLAESSNER); *Globigerina infracretacea* GLAESSNER,
893 1937, p. 28, text-fig. 1.

- 894 *Muricohedbergella planispira* (TAPPAN); *Globigerina planispira* TAPPAN, 1940, p. 12,
895 pl. 19, fig. 12.
- 896 *Praeglobotruncana delrioensis* (PLUMMER); *Globrotalia delrioensis* PLUMMER, 1931, p.
897 199, pl. 13, fig. 2a-c.
- 898 *Rotalipora cushmani* (MORROW); *Globorotalia cushmani* MORROW, 1934, p. 199, pl. 31,
899 figs 2, 4.
- 900 *Thalmaninella globotruncanoides* (Sigal); *Rotalipora globotruncanoides* Sigal, 1948,
901 p. 100, pl. 1, fig. 4, pl. 2, figs 3-5.
- 902 *Thalmaninella greenhornensis* (MORROW); *Globorotalia greenhornensis* MORROW,
903 1934, p. 199, pl. 39, fig. 1.
- 904 *Thalmaninella reicheli* (Mornod); *Globotruncana* (*Rotalipora*) *reicheli* Mornod, 1949,
905 p. 583, text-fig. 5, IVa-c.

906

907 **Figure Captions:**

908 Figure 1. Outline geological map of South-East England showing the localities
909 mentioned 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
912 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
914 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 *Thalmaninella reicheli* and *T. greenhornensis*; (22) *Praeglobotruncana* sp. cf.
923 *P. delrioensis*; (23) *Thalmaninella 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*.

931 Figure 3. Copt Point succession of the Gault Clay Formation showing the lithology,
932 ammonite zonation, foraminiferal zonation and the distribution of the various
933 superfamilies (*sensu* Loeblich and Tappan, 1964).

934 Figure 4. Distribution of stratigraphically significant foraminifera in the Glyndebourne
935 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.

939