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1 Latest Ordovician–earliest Silurian acritarchs and chitinozoans from
2 subsurface samples in Jebel Asba, Kufra Basin, SE Libya

3
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32

33 **Abstract**

34

35 Latest Ordovician–earliest Silurian Tanezzuft Formation shales recovered from core material of
36 the shallow borehole JA-2 drilled in Jebel Asba at the eastern margin of the Kufra Basin,
37 southeastern Libya, yielded well-diversified palynomorph assemblages with transparent and
38 brownish to yellowish vesicles and organic matter (visual kerogen Type 1 and 2) from depth
39 interval 46.20 to 67.82 m. In addition, miospores including cryptospores, and *Tasmanites* sp.
40 (“*Tasmanites* with nodules”), scolecodonts, and a stratigraphically significant palaeo-marker, the
41 enigmatic, tubular organic structure *Tortotubus protuberans*, were also recorded frequently in
42 most samples. Kerogen colour based on miospores (TAI <3) and chitinozoan reflectance indicate
43 an immature facies for oil generation. The two uppermost samples (from 33.33 m and 46.20 m
44 depths) and the lowermost ones (from 67.92 to 73.21 m depth) contain rare palynomorphs and
45 other organic remains and have been partially affected by oxidation.

46 Furthermore, palynological and palynofacies analysis was carried out on cuttings from an
47 old well (UN-REMSA well), ca. 530 m towards the NNE from well JA-2. The composition of
48 the organic residue is similar in both wells. However, the UN-REMSA well yields fairly
49 numerous chitinozoans, scolecodonts and biofilms but lacks the “thread-like structures” and
50 “*Tasmanites* with nodules” observed in well JA-2.

51 All the investigated samples in well JA-2 are dominated by a single chitinozoan species,
52 *Euconochitina moussegoudaensis* Paris (in Le Hérissé et al., 2013). Based on correlation with
53 chitinozoan-bearing strata around the Ordovician–Silurian boundary, the analysed samples from
54 well JA-2 and from the UN-REMSA well are regarded as post-glacial, but still of either latest
55 Hirnantian age, or at least no younger than earliest Rhuddanian. A well-diversified acritarch,

56 miospore and cryptospore assemblage recorded in well JA-2 supports a marginal marine
57 (nearshore) depositional environment. This assemblage is no older than earliest Rhuddanian yet
58 the latest Hirnantian age of the assemblage cannot be completely ruled out as our current
59 knowledge on the post-glacial, latest Hirnantian acritarch and miospore assemblages is poorly
60 documented in North Africa.

61

62 *Keywords:* biostratigraphy; acritarchs; chitinozoans; Hirnantian; Silurian, Gondwana; Libya

63

64 **Research highlights**

65 ▶ We describe palynomorphs from subsurface shales of SE Libya.

66 ▶ The shales are of latest Hirnantian–earliest Rhuddanian age.

67 ▶ The shales are immature for oil generation.

68 ▶ Dominant chitinozoan species *Euconochitina moussegoudaensis* Paris.

69 ▶ Discussion of the Ordovician–Silurian boundary.

70

71 **1. Introduction**

72

73 The precise location of the source rock horizons close to the Ordovician–Silurian boundary is an
74 important question for hydrocarbon exploration in northern Gondwana regions. In areas of
75 anoxic geological setting, typical “hot shale” horizons are easily identified by their peculiar
76 lithology (e.g., black shales), a sharp positive excursion of the gamma-ray curve in the well logs
77 and high total organic carbon (TOC) content (e.g., Lüning et al., 2000, 2005, 2006). These
78 characteristics can also be determined by the visual nature and the abundance of the organic

79 matter including palynomorphs, animal remains and associated amorphous organic matter
80 (AOM).

81 The main goal of the present study is to record for the first time moderately rich to rich
82 assemblages of acritarchs, chitinozoans, miospores and cryptospores recovered from well JA-2
83 in Jebel Asba, Kufra Basin, drilled by CASP (formerly known as Cambridge Arctic Shelf
84 Programme) in April–May 2009 (Fig. 1).

85

86 **2. Material and methods**

87

88 *2.1. Sampling*

89

90 Core samples from well JA-2 (geographic coordinates: 22°35'49.31"N, 24°7'57.10"E) drilled in
91 the Jebel Asba at the eastern margin of the Kufra Basin (Figs 1 and 2) and cuttings (single
92 sample SJS0001) from a pile of drill cuttings surrounding the borehole collar of an abandoned
93 well (geographic coordinates: 22°36'4.52"N, 24°8'4.67"E), apparently drilled by REMSA
94 (Repsol Exploración Murzuq S.A.), some 530 m NNE of well JA-2 have been investigated for
95 acritarchs and chitinozoans. However, we are not certain that the abandoned well was drilled by
96 REMSA, and therefore we name it UN-REMSA well with UN standing for uncertain. Before
97 starting the chemical processes, each core sample was observed under the binocular microscope
98 in order to collect information on its grain size, petrology, and possible macrofossils. The degree
99 of weathering of the rock sample was also evaluated as oxidation of the rock precludes the
100 preservation of the organic matter (Table 1). This information is useful to interpret low
101 chitinozoan abundances: low abundance in non-weathered and low-energy sediments is mainly
102 caused by environmental conditions and the lack of palynomorphs in weathered or high-energy

103 deposits, respectively, are due to oxidation of the organic matter, and to non-deposition of the
104 lighter particles such as acritarchs or chitinozoans.

105 In well JA-2 (Fig. 2), the lowermost core sample at 73.21 m depth is grey shale. Samples
106 from 67.97 to 69.12 m show evidence of weathering (e.g., oxidation of pyrite crystals; brownish
107 micas) in very fine light coloured sandstone and in whitish (altered?) shale. The uppermost
108 processed samples (33.33 m and 46.20 m) also display evidence of weathering (i.e. beige colour
109 of the silty shale and oxidation of the organic matter). This alternation most likely corresponds to
110 the deepest part of the sub-Recent weathering profile developed in many Saharan regions. In the
111 interval 46.60–67.59 m, the lithology is fairly constant and ranges from grey and greenish shale
112 to grey siltstone with micas. A lithological change is noticed between 67.59 and 67.82 m with
113 the occurrence of very fine sandstone. However, for the microfossils, a major change occurs at
114 67.97 m with a dramatic drop in abundance of the chitinozoans, possibly related to either the
115 oxidation, noticed in the core samples (Table 1), or to temporary emersion (e.g., during the latest
116 Hirnantian–earliest Rhuddanian post-glacial rebound), which permitted the weathering of the
117 older strata. Ground water circulation in a minor fault also might have caused oxidation of the
118 rock and of its organic matter between 67.82 and 69.12 m. Because no biostratigraphical
119 information is available on the underlying strata, it is not possible to favour one or the other of
120 these hypotheses.

121 The cutting sample SJS0001 from the UN-REMSA well is susceptible to caving.
122 However, because no strong lithological disparity was noticed in the cuttings collected and
123 investigated, the drilled horizon represents likely dark grey silty shale, which is the most
124 common component of the sample.

125

126 *2.2. Sample preparation*

127
128 The core material was split into equal parts and prepared separately for acritarch and chitinozoan
129 analysis. For the acritarchs, the samples were treated according to standard palynological
130 preparation methods. A zinc bromide solution (specific gravity 2 g cm^{-3}) was used for separation
131 of organic matter, which was then screened using a $15 \text{ }\mu\text{m}$ mesh for washing in order to separate
132 the larger organic-walled microfossils. If necessary, samples were also treated with nitric acid.
133 For chitinozoans, the processing technique developed in the palynological laboratory of Rennes
134 University (see Paris et al., 2012) was adopted. The palynological slides corresponding to the
135 illustrated material on Plates I to V are housed in the CASP Palaeontological Collection in
136 Cambridge, and the palynological slides corresponding to the illustrated material on Plates VI to
137 XII are housed in the collection of Rennes University under the repository numbers IGR 72951
138 to 72995.

139
140 **3. Palynological results**
141
142 Marine acritarchs, leiosphaerids, *Tasmanites*, land-derived plant elements (cryptospores,
143 miospores), and “thread-like structures” possibly related to cyanobacteria or to fungi in
144 association with nearshore chitinozoans, scolecodonts and eurypterid remains are reported in this
145 study (Tables 1 and 2). Large organic “blades” or “sheets”, called “biofilm”, are also present in
146 the organic residues.

147
148 *3.1. Marine phytoplankton and land-derived plant element assemblages*

149
150 *3.1.1. Species from well JA-2*

151
152 The interval 33.33–69.12 m yielded rich to moderately rich assemblages of acritarchs (Plates I to
153 IV) dominated by *Leiosphaeridia* spp. The presence of *Eupoikilofusa striatifera* at 48.18 m,
154 *Moyeria cabbotti* at 67.82 m and *Leiosphaeridia acerscrabrella* suggest an age no older than
155 Rhuddanian for this interval. Other accessory taxa present in the studied core samples include
156 *Buedingiisphaeridium* sp., *Diexallophasis denticulata*, *Filisphaeridium* sp., *Geron* cf. *gracilis*,
157 *Tunisphaeiridium* sp., *Veryhachium europaeum*, *V. lairdii* and *V. trispinosum* (Table 2).

158 The assemblage is dominated by miospores in the upper part of the interval 46.60–53.07
159 m. Tetrads and other cryptospores are dominant in the interval 48.18–67.82 m. Land-derived
160 spore tetrads are recorded in residues from various depths (see Tables 1 and 3) but mostly in the
161 interval 55.53–62.34 m. Miospores are represented by *Ambitisporites dilutus*,
162 *Archaeozonotriletes chulus* var. *chulus* and trilete spores. Cryptospores are represented by
163 *Dyadospora murusdensa*, *Rugosphaera* sp. and *Tetrahedraletes medinensis*. The presence of
164 these miospores and cryptospores are consistent with an early Silurian (Llandoveryan,
165 Rhuddanian) age for the assemblage.

166 A few scolecodonts identified to the generic level (Plate XII, 1–2, 17) are present in the
167 upper part of the core (Table 1). These jaws of marine worms (polychaetes) occur in nearshore
168 as well as in pelagic deposits. Unusual thread-like and branched structures (Plate IX, 1, 6–8;
169 Plate XII, 9, 14, 18) of unknown biological affinities (plant, cyanobacteria or fungi?) are also
170 present in the organic residues (Tables 1 and 3). They are assigned to *Tortotubus protuberans*
171 Johnson, 1985, which seems restricted to latest Ordovician–earliest Llandovery nearshore
172 deposits in northern Gondwana localities (e.g., Chad, Libya, Oman, Saudi Arabia) and North
173 America (Pennsylvania).

174 One of the peculiar characteristics of the palynological residues of JA-2 is the occurrence
175 of large “blades” or “sheets” (up to 1 mm thick) of amorphous organic matter (Plate IX, 2–5, 10;
176 Plate XII, 15-16). The chitinozoans and other palynomorphs are often adhesively associated with
177 amorphous organic matter (Plate IX, 9; Plate XI, 14–15, 17) as result of which the processes of
178 the Ancyrochitininae break frequently during sorting of the vesicles. These organic sheets are
179 composed of agglomerated minute particles of several μm in length and less than one μm thick
180 (Plate IX, 3 and 10). Pyrite framboids with 10 μm in diameter are recorded, with the exception of
181 a sole specimen of about 500 nm. Under transmitted light microscope, they appear as tiny black
182 spheres in the brownish to yellowish organic sheets. After oxidation with HNO_3 , the pyrite is
183 dissolved and the casts of the framboids are visible (Plate IX, 5 and 10). The organic sheets are
184 here called “biofilms”, produced by algae or by bacteria. The organic matter in the northern
185 Gondwana “hot shale” has a similar structure with minute “flakes” of organic particles
186 adhesively clumped with the organic-walled microfossils. However, in the JA-2 well samples,
187 the AOM is concentrated in films coating the bedding plane, whereas in the classical “hot shale”
188 this organic matter is a major component of the sediment (up to 30% in some cases). This
189 organic matter may represent remnants of algae.

190

191 3.1.2. *Species from the UN-REMSA well*

192

193 Cutting samples (SJS0001) from the UN-REMSA well, located some 530 m NNE of JA-2,
194 yielded sparse acritarchs including *Leiosphaeridia* sp. and *Eupoikilofusa striatifera* (Table 2).
195 Land-derived palynomorphs include *Ambitisporites dilutus* and a spore tetrad along with
196 *Tortotubus protuberance* (Table 3). These taxa are also present in the core samples from JA-2.

197 The sediment was deposited in a shallow marine environment. The sample is rich in AOM with
198 TAI <3, suggesting an immature kerogen with poor source potential.

199

200 3.2. Chitinozoan assemblages

201

202 3.2.1. Species from well JA-2

203

204 Most of the processed samples, except the two uppermost (33.33 and 46.20 m) and the
205 lowermost interval (67.97–73.21 m), which are likely to be affected by oxidation (see above),
206 yield well-preserved chitinozoan assemblages with transparent and brownish to yellowish
207 vesicles (Plates X–XI). They are poorly diversified and frequently monospecific assemblages
208 (see Fig. 4). However, the chitinozoan abundance is fairly high as it exceeds 100 specimens per
209 gram of rock in half of the productive samples, and even reaches 430 specimens per gram of
210 rock at 57.58 m (Fig. 2; Table 1). In the other samples, the chitinozoan abundance ranges around
211 60 to 80 specimens per gram of rock, except at 60.23 and 62.34 m depth where the abundance
212 drops significantly with 23 and 5 specimens respectively per gram of rock. It is worth noting that
213 eurypterid remains (Plate XII, 3–6) and *Tasmanites tzadiensis* Le Hérissé (in Le Hérissé et al.,
214 2013) (Plate XII, 7–8, 11–13) are associated in these two samples (Table 1). This suggests
215 shallower environments with prominent agitation in which the sediment (siltstones with large
216 micas) becomes more mobile so that a selective sorting of the lighter particles occurs.

217 All the investigated samples, except those from 67.59–67.97 and 73.21 m, are dominated
218 by a single species, *Euconochitina moussegoudaensis* Paris (in Le Hérissé et al., 2013), which
219 represents 95 to 100 % of the recovered assemblages (Fig. 4). This species dominates also the
220 chitinozoan assemblages recorded in the Moussegouda shallow core in NW Chad (Le Hérissé et

221 al., 2013) from grey silty shale intervals as in well JA-2. Furthermore, it has been described from
222 the Late Ordovician of Eastern Alborz in northern Iran (Ghavidel-Syooki, 2008).

223 *E. moussegoudaensis* is a simple form (see diagnosis and description by F. Paris in Le
224 Hérissé et al. 2013 and Plate VI, 4a–b, 8a–b; Plate VII, 5; Plate VIII, 3a-b, 4, 5a-b; Plate X, 1,
225 5–8, 10, 12, 14–16, 18; Plate XI, 16, 18-20). Its conical chamber has gently tapering flanks and a
226 flat to slightly convex bottom, which may be variously affected during the flattening (folded
227 inside or outside the chamber giving a more or less sharp aspect to the margin; see Plate X). No
228 mucron or basal scar has been observed on the available material. The sub-cylindrical neck
229 represents one third or less of the vesicle length, which ranges from ca. 100 to 200 μm . The
230 weak flexure is located at the base of prosome, near the junction of the rica on the chamber inner
231 wall (only visible on the transmitted light photos; Plate X). The wall surface is practically
232 smooth, but at high magnification, SEM observation reveals very tiny granules (Plate VI, 4b),
233 which are better expressed on, or near the margin (Plate VI, 8b). This species has no highly
234 distinctive features (i.e., ornamentation). However, it can be identified on large populations
235 allowing the appraisal of the intraspecific morphological variations.

236 During the present study, elongate specimens sharing most of the characters of *E.*
237 *moussegoudaensis* Paris have been observed together with the typical form. These slender
238 individuals are tentatively separated from the main morphotype. They are referred to as
239 *Euconochitina* cf. *moussegoudaensis* Paris in Fig. 4 and on Plate X, 2–3, 9, 11, 19–20 and Plate
240 XI, 3, 5, 11. The vesicle length exceeds 200 μm and may reach 230 μm . A weak constriction is
241 visible at a short distance above the margin (e.g., Plate X, 2, 19–20). It is not clear yet if these
242 elongate and slender vesicles correspond to the end forms within a polymorphic species or if
243 they represent a different species, with a stratigraphical range partly overlapping the total range
244 of *E. moussegoudaensis* Paris.

245 Besides the dominating *E. mousseghoudaensis* Paris are subordinate species restricted to
246 one or two samples. *Calpichitina* sp. (Plate X, 13) is restricted to one specimen recorded at 66.85
247 m depth. The membranous remains visible on the margin are most likely residues of the biofilm
248 somehow glue the vesicle, and not part of a carina as in *Pterochitina deichaii*.

249 Two species of *Spinachitina* – *S. oulebsiri* Paris et al. (2000) and *Spinachitina verniersi*
250 Vandenbroucke in Vandenbroucke et al. (2009) – are recorded in well JA-2. For the former, the
251 most abundant population is from 67.59 m (Fig. 4) but a few individuals are also recorded at
252 67.21 and 67.40 m. *Spinachitina oulebsiri* (Plate VII, 1a–c, 3a–b, 4a–b, 6, 8 and 9a–c; Plate XI,
253 1, 6–10) has a conical chamber and a rather short sub-cylindrical neck (about one third of the
254 vesicle length) ended with a denticulate aperture (Plate VII, 9c). The margin bears a crown of ca.
255 20 slender conical spines of up to 6 μm length (Plate VII, 1b, 3b, 4b and 9b). Butcher (2009, p.
256 600) included *S. oulebsiri* in the synonymy list of *S. fragilis*, which is the index species for the
257 first Silurian chitinozoan biozone (Verniers et al., 1995). Even if they have close silhouettes, we
258 do not consider the two species as synonyms. This is in agreement with Vandenbroucke et al.
259 (2009) who reported *S. oulebsiri* from South Africa (see below). Indeed, *S. oulebsiri* has not the
260 conspicuous shoulder of the specimens Butcher assigned to *S. fragilis* from depth 42.50 m in
261 BG-14 in Jordan. Moreover, the populations of *S. oulebsiri* known in various localities from
262 Algeria (Paris et al., 2000; F. Paris, unpublished data) and South Africa (Vandenbroucke et al.,
263 2009) do not include large specimens ($>250 \mu\text{m}$) as known in *S. fragilis*. Based on the discussion
264 below, *S. oulebsiri* ranges from the late Hirnantian to possibly earliest Rhuddanian (see Fig. 5).
265 Poorly preserved individuals from 62.34 m are tentatively referred to *S. sp. aff. oulebsiri*.

266 In well JA-2 (Fig. 4), *Spinachitina verniersi* Vandenbroucke (in Vandenbroucke et al.,
267 2009) (Plate VI, 3a–b; Plate VII, 2a–b) is fairly abundant at 67.59 m and is represented by a few
268 individuals at 65.74 m (see Fig. 4). This species, first described from the Soom Shale in South

269 Africa (Vandenbroucke et al., 2009), has a vesicle very close to that of *S. oulebsiri* and even to
270 that of *E. moussegoudaensis* Paris. However, it is clearly distinguished from *S. oulebsiri* by the
271 design of the crown of ornaments running on its margin (more densely spaced and irregular
272 granules or blunt spines) (see Plate VII, 2a). Closely related specimens (*S. cf. verniersi*; Plate XI,
273 4) or more questionable individuals referred to as ?*S. verniersi* (Plate VI, 1a–b, 2a–b, 6a–b,
274 7a–b; Plate VII, 7) due to a poor preservation of the crown on the margin are scattered from
275 55.53 m depth to 67.82 m depth in well JA-2 (Fig. 4). *S. verniersi* does not benefit yet from an
276 accurate independent calibration by means of graptolites. However, in South Africa its FAD
277 (First Appearance Datum) is in the Soom Shale Formation, i.e. just above the last Hirnantian
278 glacial deposits (see discussion in Vandenbroucke et al., 2009). In Algeria, it also coexists with
279 *S. oulebsiri* in the M'Kratta Formation above the Hirnantian diamictites of the Hassi el Hadjar
280 Formation (see discussion in Paris et al., 2000). *S. verniersi* is also recorded in the cuttings from
281 the UN-REMSA well (Plate VIII, 6a–c, 9a–b, 10a–b) where it occurs in association with *E.*
282 *moussegoudaensis* Paris.

283 The Ancyrochitinae, abundant at 67.82 m depth, are present sporadically. *Plectochitina*
284 sp. (Fig. 4) is another form kept in open nomenclature because of its poor preservation. They
285 belong possibly to *Plectochitina cf. longispina* (Achab, 1978), which is the dominating species
286 at 67.82 m depth (Plate VI, 5, 10; Plate XI, 13–15, 17). These specimens are assigned to
287 *Plectochitina* rather than to *Ancyrochitina* because of the cell-like structure of their long
288 processes (Plate X, 15 and 17). The individuals recorded at 67.82 m depth are rather small, e.g.
289 vesicle length ranging from 100 to 120 µm. The length of the processes is about 40 to 60 µm.
290 These values are very close to the measurements of *Ancyrochitina longispina* described by
291 Achab (1978) in the Ellis Bay Formation of Anticosti Island, Eastern Canada. The Libyan and
292 the Canadian specimens have processes with similar branching. The main difference between the

293 two populations is the less developed branching of the Libyan individuals (2 times branching as
294 a maximum). According to Achab (1978) and Soufiane and Achab (2000), *A. longispina* is
295 restricted to the lower member of the Ellis Bay Formation assigned to the early Hirnantian (i.e.
296 *extraordinarius* graptolite Zone) by Melchin (2008). Recently, Butcher (2009) published a form
297 he called *Ancyrochitina* sp. C, which displays most of the features of the individuals identified
298 here as *Plectochitina* cf. *longispina*, i.e. short vesicle. However, the form illustrated by Butcher
299 (2009) from BG-14 in Jordan is from the upper *ascensus*–*acuminatus* Biozone (early
300 Rhuddanian). Obviously, there is an urgent need of clarification of the Ancyrochitinae close to
301 the Ordovician–Silurian boundary, especially the forms with long processes.

302

303 3.2.2. *Species from the UN-REMSA well*

304

305 The composition of its organic residue is very similar to most of the residues recovered from
306 well JA-2. It includes fairly numerous chitinozoans, scolecodonts and biofilms. However, neither
307 “thread-like structures”, nor “*Tasmanites* with nodules” (i.e. *Tasmanites tzadiensis* Le Hérisse in
308 Le Hérisse et al. 2013) have been observed in this residue.

309 The cuttings from the UN-REMSA well (sample SJS0001) yield a chitinozoan assemblage very
310 close to that observed in well JA-2. *Euconochitina moussegoudaensis* Paris (Plate VIII, 2a–b; 4,
311 5a–b) is again the dominant species. It is accompanied by rare *Cyathochitina caputoi* Da Costa,
312 1971 (Plate VIII, 1). *C. caputoi* (the thick carina form), which is usually very abundant close to
313 the Ordovician–Silurian boundary is not observed in well JA-2. A few *Spinachitina verniersi*
314 (Plate VIII, 6a–c, 9a–b, 10a–b) and damaged Ancyrochitinae (Plate VIII, 7–8) (broken
315 processes do not allow any specific assignment) are also present in this assemblage and are
316 assigned to the latest Hirnantian–earliest Rhuddanian (see Fig. 5).

317
318 *3.3. Kerogen analysis and thermal maturity*
319
320 Visual kerogen analysis using transmitted light microscopy was carried out on 23 samples from
321 the interval 33.33–73.21 m (Table 4). The analysis results are summarised in Figure 2. The
322 interval 33.33–46.20 m is completely dominated by semi-structured (Type 3), vitrinite-like
323 material. No acritarchs or miospores were recorded in this interval. The interval 46.60–67.40 m
324 is generally dominated by AOM (Type 1) but semi-structured, vitrinite-like material continues to
325 show its presence throughout the interval (see Appendix A). A high number of acritarchs along
326 with miospores/cryptospores are also documented. *Leiospheridia* spp. dominate in numbers, and
327 spiny acanthomorph acritarchs are low in numbers. The interval 67.59–73.21 m, with the
328 exception of core at 69.92 m depth, in which AOM dominates, is abundant in semi-structured,
329 vitrinite-like material.

330 Based on the colour of the miospores, the thermal alteration index (TAI) (Staplin, 1969)
331 is less than 3, indicating an immature palynofacies for oil generation. Acritarchs and
332 cryptospores are consistently pale and light yellow in colour, which probably indicates a lack of
333 thermal alteration. Chitinozoan reflectance yielded R_{ch} values of about 0.6% (Table 5) which
334 equals vitrinite reflectance (R_v) values of about 0.4% when using the equation of Tricker et al.
335 (1992). Sediment with R_v of 0.4% is immature for oil generation, supporting the TAI
336 interpretation.

337

338 **4. Biostratigraphy, palaeoecology and regional correlation**

339

340 *4.1. Marine phytoplankton and land-derived plant element assemblages*

341

342 The acritarchs assemblage is dominated by thin-walled *Leiosphaeridia* spp. often in clusters.

343 Dorning (1981) found dominance of thin-walled leiosphaerids in the shallow marine Silurian

344 (Ludlovian) sequence of the Welsh Borderland. The presence of land-derived vitrinite-like

345 macerals and miospores–cryptospores is also indicative of a marginal marine (nearshore)

346 depositional environment for the entire sequence of the studied well JA-2, although the interval

347 33.33–60.23 m does seem much closer to land with the dominance of land-derived plant

348 remains.

349 In the late Silurian of the Ghadamis Basin, Al-Ameri (1983) erected six distinct types of

350 palynofacies of which four contained acritarchs indicating increasing distance from the

351 shoreline. Hill and Molyneux (1988) recognised two Llandoveryian palynofacies assemblages in

352 NE Libya. Their southern assemblage located in southern Cyrenaica, north of the present study

353 area, was also dominated by leiosphaerids. Hill and Molyneux (1988) consider their acritarch

354 assemblage comparable most closely to Palynofacies 3 of Al-Ameri (1983), which is interpreted

355 as inner neritic.

356 The studied assemblage is also comparable to the land-derived palynoflora (miospores–

357 cryptospores and organic structures) of early Silurian (Rhuddanian) age from the Tuscarora

358 Formation in central Pennsylvania, USA (Johnson, 1985). Based on these comparisons the

359 present assemblage was probably deposited closer to the shoreline.

360

361 *4.1.1. Libya*

362

363 Acritarch assemblages recorded in well JA-2 are similar to those from other basins in North

364 Africa, the Middle East, and North America (Fig. 3).

365
366 Kufra Basin
367
368 Grignani et al. (1991) established a zonation of the early Silurian Assemblage C based on the
369 chitinozoan *Ancyrochitina ancyrea*. However, the authors reported no early Silurian acritarchs.
370 The marker acritarchs such as *Villosacapsula irrorata*, *V. setosapellicula* and *Veryhachium*
371 *subglobosum* restricted to the Late Ordovician (Caradoc–Ashgill) were reported by Grignani et
372 al. (1991) and by Thusu et al. (2007) from cutting samples from Jebel Dalma.
373
374 Murzuq Basin
375
376 Paris et al. (2012) reported an early Llandovery palynomorph assemblage from well CDEG-2a in
377 Dor el Gussa and recorded palynomorph species which are also present in the present study
378 including *Buedingiisphaeridium* sp., *Diexallophasis denticulate*, *Eupoikilofusa striatifera*,
379 *Leiofusa estrecha*, *Veryhachium. europaeum*, *V. trispinosum*, *Dyodospora murusdensa* and
380 *Tetraedraletes medinensis*.
381
382 Ghadamis Basin
383
384 Richardson and Ioannides (1973) reported a rich assemblage of Silurian acritarchs from two
385 wells, C1-34 and B2-34, from the Akakus and Tanezzuft formations in the Ghadamis Basin. The
386 recorded species in common with the present assemblage include *Eupoikilofusa striatifera*,
387 *Veryhachium trispinosum*, *Diexallophasis denticulata*, *Leiosphaeridia acerscabrella*, *Leiofusa*
388 *estrecha*, *Geron* cf. *gracilis*, *Tetraedraletes medinensis* and *Dyadospora murusdensa*.

389
390 Northeast Libya, Cyrenaica
391
392 Hill et al. (1985), Hill and Molyneux (1988) and Richardson (1988) recorded early Silurian
393 (Llandoveryan) acritarchs from the Cyrenaica Platform. Several species recorded from Cyrenaica
394 are common with the present assemblage and include *Eupoikilofusa striatifera*, *Diexallophasis*
395 *denticulata*, *Tunisphaeridium* sp., and *Buedingiisphaeridium* sp..

396
397 *4.1.2. Chad*

398
399 Le Hérissé et al. (2013) reported latest Ordovician–earliest Silurian palynological assemblages
400 from the Moussegouda shallow borehole (21°40'N, 18°36'E) drilled in the Erdi Basin, northern
401 Chad in the early 1960s. The Erdi Basin and the Mourdi Basin in northwest Sudan are
402 considered to be the southern extensions of the Kufra Basin to the north in Libya.
403 The presence of several stratigraphically restricted acritarchs reported from core 9 (220–221A
404 m) from the Moussegouda borehole such as *Neoveryhachium* sp. A, *Veryhachium subglobosum*
405 and *Villosacapsula setosapellicula* clearly support an age no younger than Late Ashgill for this
406 interval. *V. subglobosum* and *V. setosapellicula* were also recorded by Grignani et al. (1991) in
407 their assemblage 'B' in the Kufra Basin. None of these species were recorded in our study. The
408 absence (except in the basal part) of these species together with the common presence of
409 *Tasmanites tzadiaensis* Le Hérissé et al. (2013) and many reported acritarchs and chitinozoans,
410 cryptospores and miospores in cores 8–2 from the Moussegouda well in Chad and those in well
411 JA-2 in Libya support their close chronostratigraphic and ecological similarities.

412 The oldest recorded early Silurian (late Rhuddanian) local Biozone LI1 was first reported by Hill
413 and Molyneaux (1988) from an exploratory well (E1-81) in Cyrenaica northeast Libya and
414 recently by Paris et al. (2012) from a shallow borehole (CDEG-2) in Dor el Gussa, eastern
415 Murzuq Basin. In both areas, the incoming of marker species *Diexallophasis caperoradiola*,
416 *Multiplicisphaeridium fisherii* and *Oppilatala eoplanktonica* clearly support a Late Rhuddanian
417 age. None of these species were either recorded in Le Hérissé et al. (2013) in the Moussegouda
418 well or in the present study in the JA-2 well. Based on these observations, it is inferred that the
419 post-Ashgillian interval in the Moussegouda well (cores 8–2) and in well JA-2 may represent a
420 time interval between the latest Ordovician and earliest Silurian. However, the presence of
421 *Geron cf. gracilis*, *Moyeria cabotii*, *Tunisphaeridium* sp., *Ambitisporites dilutus* and
422 *Archaeozonotriletes chulus* var. *chulus* and *Tortotubus protuberans* in well JA-2 does appear to
423 demonstrate an early Silurian age for the JA-2 assemblage. Furthermore, we cannot rule out the
424 extension of the well JA-2 sequence to the post-glacial latest Hirnantian because the post-glacial
425 latest Hirnantian acritarch and miospore assemblage is poorly documented in North Africa.
426 The palynomorph content in both wells is supportive of a marginal marine (nearshore)
427 environment and may represent a post-glacial pre-Tanezzuft Formation (sensu stricto)
428 sedimentary sequence.

429

430 4.1.3. Algeria

431

432 Jardine et al. (1974) recorded early Silurian acritarch assemblages from the Algerian Sahara and
433 established Palynozones G1 and G2. Species common to the Algerian and present assemblage
434 include *Diexallophasis denticulate*, *Eupoikilofusa striatifera*, *Leiofusa estrecha* and
435 *Veryhachium trispinosum*.

436
437 *4.1.4. Saudi Arabia*
438
439 Le Hérissé et al. (1995) recorded early Silurian (Llandovery, Rhuddanian and Aeronian)
440 palynomorphs assemblage from Saudi Arabia. They recorded *Buedingiisphaeridium* sp., *D.*
441 *denticulata*, *E. striatifera*, *Filisphaeridium* sp., *Geron* sp., *Moyeria cabottii* and *Tunisphaeridium*
442 sp..

443
444 *4.1.5. Jordan*
445
446 Keegan et al. (1990) recorded early Silurian palynomorphs from two exploration wells of the
447 Hashemite Kingdom of Jordan. The morphotypes *Geron gracilis*, *D. murusdensa*, *Ambitisporites*
448 *dilutus* and *Archaeozonotriletes chulus* var. *chulus* are present in zone JS-3 (early Llandoveryan)
449 of Jordan and are also recorded in the present study.

450
451 *4.1.6. North America*
452
453 The studied assemblage in well JA-2 is closely comparable with the early Silurian (Rhuddanian)
454 assemblage from the Tuscarora Formation in central Pennsylvania, USA (Johnson, 1985).
455 Common species include *L. acerscabrella*, *T. mediensis*, *A. dilutus*, *Rugosphaera* cf.
456 *tuscarorensis* and *Tortotubus protuberans*.

457
458 *4.2. Chitinozoan assemblages*

459

460 Available data on chitinozoans from the Ordovician–Silurian boundary increased significantly
461 during the last ten years with the work of Bourahrouh (2002) (data on Algeria, Morocco, western
462 France and Czech Republic) and the papers of Vandenbroucke et al. (2009) on the chitinozoans
463 from the Soom Shale of South Africa, and of Butcher (2009) on those of the Mudawwara Shale
464 Formation in Jordan. A few new species are erected in these contributions. However, an
465 extensive taxonomical study of many undescribed new forms from the Late Ordovician–early
466 Silurian of northern Gondwana regions, based on large populations, is now urgently needed.
467 Independent biostratigraphical control by means of graptolites is now available for some
468 chitinozoan-bearing sections, e.g. Nseirat section, Mauritania (Underwood et al., 1998; Legrand,
469 2009), Jordan (Lüning et al., 2006; Loydell, 2007, 2012), Les Fresnaies section, southern
470 Brittany, France (Piçarra et al., 2009), and Hlasna Treban, Czech Republic (Štorch, 1996; Štorch
471 and Loydell, 1996). All these data now allow a reassessment of the chitinozoan assemblages
472 formerly described in NE Libya by Molyneux and Paris (1985) and by Paris (1988).
473 The occurrence of chitinozoans throughout the penetrated sequence in JA-2 (except the barren
474 lowermost samples; see above) clearly indicates a marine deposit. The rather low diversity of the
475 recorded assemblages, in spite of high abundance (up to 415 specimens per gram of rock), is
476 compatible with deposition in a rather proximal setting to the shoreline. This is consistent also
477 with the occurrence of land-derived cryptospores and miospores in association with vitrinite-like
478 organic matter in the residues. The presence of eurypterids (Plate XII, 3–6) is also in favour of
479 environments not very far from the shoreline as these animals are regarded as nearshore (e.g.,
480 Jones and Kjellesvig-Waering, 1985), and in some cases occasionally terrestrial organisms
481 (especially in the late Silurian) (e.g., Braddy, 2001). The occurrence of *Tortotubus protuberans*
482 (Plate XII, 9, 14, 18) provides an additional indication of deposition fairly close to the shoreline,

483 as this enigmatic microfossil is usually reported from shallow to terrestrial environments at the
484 Ordovician–Silurian boundary (e.g., Le Hérissé et al., 2013).

485

486 *4.3. Ordovician–Silurian boundary*

487

488 The definition of the base of the Silurian, and thus of the Rhuddanian Stage is a critical point for
489 the calibration of the latest Ordovician–earliest Silurian chitinozoan assemblages. The
490 Ordovician–Silurian boundary first moved from its historical position at the base of the
491 *persculptus* Biozone, to the base of the succeeding *acuminatus* Biozone, with the GSSP of the
492 base of the Silurian defined at Dob’s Linn in Scotland (see Williams and Ingham, 1989). The
493 basal Silurian *acuminatus* Biozone at Dob’s Linn was subsequently subdivided into a lower
494 *Akidograptus ascensus* Biozone and a higher, more restricted *Parakidograptus acuminatus*
495 Biozone (Melchin and Williams, 2000). As a consequence, the base of the Silurian (base of the
496 Rhuddanian) is now defined by the first appearance of *A. ascensus*. This definition was ratified
497 by the International Subcommission on Silurian Stratigraphy (2007). Moreover, recent revisions of
498 graptolites from the *ascensus–acuminatus* Biozone (e.g., Loydell, 2007, 2012, and references
499 therein) confirm the three-fold divisions of this biozone by Štorch (1996) into lower, middle and
500 upper subzones. In this scheme (see Loydell, 2007, p. 10), *A. ascensus* ranges in the lower and
501 the middle subzones. All these successive changes had consequences on the accurate dating of
502 the chitinozoan biozones around the Ordovician–Silurian boundary, as there are no direct ties
503 with the GSSP at Dob’s Linn (no workable chitinozoan assemblages are available yet; see
504 Verniers and Vandenbroucke, 2006). Delabroye and Vecoli (2010) briefly reviewed the
505 biostratigraphical inconsistencies persisting in the main diagnostic fossil groups close to the
506 Ordovician–Silurian boundary.

507
508 *4.4. Chronostratigraphical calibration of the Hirnantian and Rhuddanian chitinozoan biozones*
509
510 Continuous chitinozoan-bearing strata of latest Ordovician to early Silurian age, i.e. not
511 disturbed by Hirnantian glacial events, are very rare in northern Gondwana regions (including
512 peri-Gondwana Europe, sensu Štorch, 1996). At a few localities this boundary can be located
513 with the greatest precision, for example, in the Nseirat section in the Hodh area (Mauritania),
514 which yielded associated abundant graptolites (Underwood et al., 1998; Legrand, 2009) and
515 chitinozoans (Paris et al., 1998; F. Paris, unpublished data). The Hlasna Treban section in the
516 Prague Basin (Czech Republic) also yielded well studied graptolites (Štorch, 1996; Štorch and
517 Loydell, 1996) and chitinozoan data (Dufka and Fatka, 1993; Bourahrouh, 2002). Another
518 section is at les Fresnaies, Ancenis Basin, western France, where Hirnantian chitinozoan-bearing
519 diamictites (Bourahrouh, 2002; F. Paris, unpublished data) are overlain by Rhuddanian black
520 shale with associated graptolites and chitinozoans (Bourahrouh, 2002; Piçarra et al., 2002;
521 Piçarra et al., 2009; F. Paris, unpublished data). The Ordovician–Silurian boundary can also be
522 located with the greatest precision in well BG-14 in southern Jordan where graptolites (Loydell,
523 2007) and chitinozoan (Butcher, 2009) have been studied. In southern Saudi Arabia chitinozoans
524 occur in the MKSR-1 well, just below and within graptolite-bearing black shale assigned to the
525 early Rhuddanian (Paris et al., 1995). Other important controls should be obtained from the
526 graptolite-bearing sequence in the E1-NC174 core in the Murzuq Basin (Libya) as chitinozoans
527 are also reported (Butcher, 2012) with abundant early Rhuddanian graptolites (Loydell, 2012).
528 The concurrent ranges of the chitinozoans and graptolites in these sections are used here for
529 more precise dating of numerous previously published chitinozoan assemblages close to the
530 Ordovician–Silurian boundary (Fig. 5).

531 In the present study on core samples from JA-2, the comparison focuses chiefly on the
532 chitinozoan data available for Libya, with a particular attention paid to the chitinozoan
533 assemblages from the Kufra Basin, e.g. KW-2 core-drill (Grignani et al., 1991; Le Hérissé et al.,
534 2013; F. Paris, unpublished data), cores from wells A1-NC43 and B1-NC43 (Grignani et al.,
535 1991), and cuttings from H6000 and W5174 (Paris et al., 2008) (Fig. 5). Correlation is also
536 proposed with other Libyan regions, e.g. well CDEG-2a in the eastern Murzuq Basin (Paris et
537 al., 2012). The Silurian chitinozoans of Al-Ameri (1989) from Western Libya, however, are not
538 discussed here as they correspond to assemblages younger than the material recovered from the
539 sub-surface of the Kufra Basin. Older data from Cyrenaica (Molyneux and Paris, 1985; Paris,
540 1988), which did not benefit from an independent calibration in terms of graptolite biozones, can
541 now be updated. The correlations are extended to cores in other countries, e.g. Moussegouda,
542 northern Chad (Le Hérissé et al., 2004, 2013).

543 In Moussegouda, the occurrence of glacio-marine deposits with typical Late Ordovician
544 chitinozoans and acritarchs ca. 15 m below the first *E. moussegoudaensis* chitinozoan
545 assemblage must be stressed, as this demonstrates that the *E. moussegoudaensis* dominated
546 assemblage is clearly post-glacial. In well KW-2, *E. moussegoudaensis* occurs in the shale
547 referred to the Tanezzuft Formation (Le Hérissé et al., 2013). Below 54 m of this Tanezzuft
548 Formation shale, the well penetrated sandstone of the Mamuniyat Formation for 7 m. No
549 chitinozoans are reported from this sandy member but typical latest Ordovician chitinozoan
550 assemblages are present in the neighbouring wells of A1-NC43 (core 3, Mamuniyat Formation)
551 and B1-NC43 (core 5; but supposed to belong to the Tanezzuft Formation in Grignani et al.,
552 1991). The lithostratigraphic position of the latter core sample, however, is confusing (see
553 discussion in Grignani et al., 1991, p. 1163). No graptolites have been identified in JA-2 or in
554 Moussegouda, but Grignani et al. (1991) reported “*Climacograptus medius*” (now

555 *Normalograptus medius*) in the KW-2 cores. If the identification is correct, this means that the
556 corresponding samples can be of late Hirnantian as well as of Rhuddanian age as this species
557 ranges across the Ordovician–Silurian boundary (see Loydell, 2007, text in fig. 6). In areas of
558 JA-2 and KW-2, we do not have unweathered material from the overlying formations. In
559 Moussegouda, the shale sequence with the *moussegoudaensis* chitinozoan assemblage is directly
560 overlain by barren white sandstone referred to the Akakus Formation. No biostratigraphical data
561 are available in the Silurian part of A1-NC43 and B1-NC43. Consequently, the top of the
562 *moussegoudaensis* assemblage is not constrained in the Kufra Basin, even when this structure is
563 extended to northern Chad.

564 The ranges of *S. oulebsiri* and *S. verniersi*, two taxa represented in the *moussegoudaensis*
565 assemblage, have been used to better constrain its chronostratigraphic assignment. *S. oulebsiri*
566 ranges in late Hirnantian post-glacial deposits, especially in the Nseirat section (Mauritania),
567 where it coexists briefly with *Belonechitina pseudarabiensis* and *Cyathochitina caputoi*. The
568 latter have their Last Appearance Datum (LAD) higher up in the section in the well-dated upper
569 *ascensus–acuminatus* Biozone of early Rhuddanian age. The lower part of the Nseirat section
570 (with *S. oulebsiri*) yields abundant *Normalograptus* graptolites attributed to the *persculptus*
571 Biozone (Underwood et al., 1998), i.e. of late Hirnantian age. However, the specific assignment
572 of these *Normalograptus* have been recently contested by Loydell (2007) who rejected the
573 specimens of *N. persculptus* illustrated by Underwood et al. (1998) from his well-documented
574 synonymy list for *N. persculptus* (Loydell, 2007, p. 43).

575 Because the durations of the related glacial events are significantly shorter (ca. 10 ky)
576 than the range of the recorded chitinozoan species (ca. 1 Ma or more), the Hirnantian glacial
577 climax can be regarded as isochronous at the scale of the northern Gondwana chitinozoan
578 biozonations. Indeed, several typical Late Katian species, e.g. *Calpichitina lenticularis*,

579 *Armoricochitina nigerica*, *Desmochitina* gr. *minor*, *Lagenochitina baltica*, *L. prussica* (see Paris
580 et al., 2000, and references therein) range through the Hirnantian, up to the end of the main
581 melting phase of the ice cap, in the latest Hirnantian. Fortunately, some taxa have a more
582 restricted range and proved to be helpful for subdividing the latest Ordovician. *Tanuchitina*
583 *elongata*, the index species of the next to last Ordovician chitinozoan biozone (Paris, 1990) has
584 its FAD before the first drastic sea level fall characterising the beginning of the Hirnantian
585 glacial climax. This FAD is located just above the base of the Hirnantian as documented in the
586 Anti-Atlas, Morocco (Loi et al., 2010) and in the Prague Basin by Bourahrouh (2002) where *T.*
587 *elongata* is recorded in association with *Normalograptus osjuensis*. The latter graptolite is
588 regarded as slightly preceding the FAD of *N. extraordinarius*, the index graptolite of the base of
589 the “new” Hirnantian stage (see Chen et al., 2000, 2006) and thus *T. elongata* begins also just
590 below the base of the Hirnantian. The species is recorded up to the uppermost Kosov Formation
591 (Hirnantian) in the Prague Basin (Bourahrouh, 2002) where *N. persculptus* is present (Štorch and
592 Loydell, 1996). The total range of *T. elongata* is therefore latest Katian–late Hirnantian.

593 At present, *Spinachitina oulebsiri* Biozone is the last Ordovician chitinozoan biozone in
594 the northern Gondwana biozonation (Webby et al., 2004). This species coexists for a time with
595 the last typical Ordovician chitinozoan species (see above) and thus its lower part is late
596 Hirnantian in age. The LAD of *S. oulebsiri* is documented in the lower part of the Nseirat section
597 (up to MSE-10) where it is associated with other chitinozoans with dominating *Cyathochitina*
598 *caputoi* and rare *Belonechitina pseudarabiensis*. This chitinozoan assemblage coexists with
599 numerous *Normalograptus* assigned to *N. persculptus* by Underwood et al. (1998), but not
600 included in the synonymy list of this species proposed by Loydell (2007). Additional
601 information is available from the MKSR-1 well (southern Saudi Arabia) where *S. oulebsiri* is
602 restricted to strata below the ‘hot shale’ horizon yielding numerous *C. caputoi* associated with

603 graptolites of the *acuminatus* Zone (Paris et al., 1995, and discussion in Paris et al., 2013).
604 According to the graptolites, *S. oulebsiri* may therefore extend into the uppermost Hirnantian or
605 the lowermost Rhuddanian. Based on the synonymy proposed by Vandenbroucke et al. (2009),
606 *S. oulebsiri* is present in the United Kingdom (Vandenbroucke et al., 2005; Vandenbroucke,
607 2008). This species is reported from other localities devoid of accurate independent age control,
608 e.g. Soom Shale in South Africa (Vandenbroucke et al., 2009), several wells in Algeria,
609 including NI-2 (Paris et al., 2000), and sections in Argentina (De La Puente, 2009). It is also
610 present in JA-2 in SE Libya (see Fig. 4). In these localities, it is worth noting that *S. oulebsiri*
611 without the typical Late Ordovician species but associated with *S. verniersi*, occurs in post-
612 glacial deposits. This confirms that the climax of the Late Ordovician glaciation ended within the
613 *persculptus* Biozone.

614 Slightly higher in the Nseirat section (from NSE-11 to NSE-18) *B. pseudarabiensis* and
615 *C. caputoi* dominate the chitinozoan assemblages. They are associated with *S. debbajae* in strata
616 referred to the lower-middle subzone of the *ascensus–acuminatus* Biozone based on its
617 graptolite content (Underwood et al., 1998) and on the comments provided by Loydell (2007).
618 From NSE-18 onward, *B. pseudarabiensis* is associated with *S. fragilis* (morphotype with a
619 shoulder) and with graptolites of the *ascensus–acuminatus* Biozone from NSE-18. A similar
620 situation occurs also in Jordan (Butcher, 2009), in BG-14 core sample at 42.5 m depth assigned
621 by Loydell (2007) to the upper subzone *ascensus–acuminatus* Biozone. In the Les Fesnaies
622 section, western France (Bourahrouh, 2002; F. Paris, unpublished data), and in Hlasna Treban
623 section, Czech Republic (Dufka and Fatka, 1993; Bourahrouh, 2002) identical *S. fragilis*
624 specimens are associated with graptolites of the *ascensus–acuminatus* graptolite Biozone
625 described respectively by Piçarra et al. (2009) and by Štorch (1996).

626 In Libya, in the Murzuq Basin, a chitinozoan assemblage similar to that of the upper
627 middle part of the Nseirat section, i.e. *S. fragilis* “with shoulder” associated with
628 Ancyrochitinae specimens with long branched processes (provisionally identified as *A. cf.*
629 *ramosaspina*) is reported from the interval 47.48–50.64 m (core 20 to core 23) in well CDGE-2a
630 (see Paris et al., 2012). In the Kufra Basin, in cuttings samples (W5174 and H6000) abundant *B.*
631 *pseudarabiensis* coexist with Ancyrochitinae (long processes branched at their distal end,
632 provisionally referred to as *A. gr. ancyrea* in Paris et al. (2008a). Based on the chitinozoan data
633 from Jordan newly published by Butcher (2009) on BG-14 core samples accurately dated by
634 graptolites (Loydell, 2007), the two Kufra assemblages from W5174 and H6000 can be
635 correlated with the upper part of the *ascensus–acuminatus* graptolite Biozone of Jordan, where
636 *S. fragilis* is no longer present (Butcher, 2009, text in fig. 7).

637 The re-evaluation of previous chitinozoans from Libya enables more accurate dates for
638 assemblages. For instance, the chitinozoans recovered from JI-81A, E1-81 and A1-81 wells of
639 southern Cyrenaica (Molyneux and Paris, 1985; Hill et al., 1985; Paris, 1988) are updated with
640 regards to the range of the chitinozoan key species selected in the present report (Fig. 5). In well
641 JI-81A, cuttings from 12150 ft to 13240 ft, yielded caved specimens of *S. debbajae*, *S. oulebsiri*,
642 and *E. moussegoudaensis* mixed with well-characterised in-situ Hirnantian species. This means
643 that below the Middle Devonian, and above the Upper Ordovician strata, this well penetrated
644 Rhuddanian deposits (see stratigraphical interpretation on Figure 5). In well E1-81, the
645 Ordovician–Silurian beds seem rather better developed, as there is a large interval of ca. 100 m
646 separating core 4 of early Rhuddanian age (abundant *Sphaerochitina solitudina* consistent with
647 the upper subzone of the *ascensus–acuminatus* Biozone), from core 5 of Hirnantian age
648 (*elongata* Biozone) (Fig. 5).

649

650 **5. Conclusions**

651

652 The chitinozoan assemblages recovered from the 35 m thick shaly to silty sequence in well JA-2
653 are characterised by dominant *Euconochitina moussegoudaensis* and by the sporadic, but
654 stratigraphically important presence of *Spinachitina oulebsiri*, *S. verniersi*, and highly branched
655 Angochitiniinae. These characteristics are shared by the chitinozoan assemblages observed in the
656 ca. 100 m thick shale dominated sequence penetrated by the Moussegouda well (northern Chad;
657 Le Hérissé et al., 2013) and in the 4 core samples analysed previously in the KW-2 shallow core
658 (Kufra Basin, Libya; see Grignani et al., 1991; F. Paris in Le Hérissé et al., 2013). The
659 Moussegouda area is geologically regarded as part of the Kufra Basin (see e.g., Lüning et al.,
660 2006) and therefore, the more complete data available on this well can be of some help in
661 interpreting the core from well JA-2 and cuttings from the UN-REMSA well where the
662 overlying and underlying strata are not documented by samples.

663 The analysed samples from well JA-2 and the UN-REMSA well are regarded as post
664 glacial, but are still either of latest Hirnantian age, or at least no younger than earliest
665 Rhuddanian if one follows Loydell's (2007) arguments for the Mauritania material. This
666 uncertainty is indicated by a blue stripe on the graph (Fig. 5) summarising the reassessment of
667 previously reported chitinozoan assemblages from Libya. However, an alternative interpretation,
668 based on an environmental control of the range of the chitinozoans, cannot be definitively ruled
669 out, even if the chitinozoans are not usually deeply affected by environmental factors. Because
670 the *moussegoudensis* chitinozoan assemblages are so far restricted to the rather nearshore
671 environments of the Kufra Basin (including Chad), the proliferation of *E. moussegoudaensis*
672 may reflect an environmental control rather than a stratigraphically restricted range. If so, the
673 absence of *E. moussegoudaensis* in Rhuddanian sections with a graptolite control (deeper

674 environments) would simply be a result of differences in the bathymetry of the depositional
675 areas.

676 Based on the discussion above on chitinozoan biostratigraphy and palaeoecology, it
677 appears that the studied section records an assemblage of latest Ordovician to earliest Silurian
678 age. The acritarchs, miospores and cryptospores assemblage recorded seem to be no older than
679 earliest Rhuddanian. However, several key post-glacial, latest Hirnantian sections, especially the
680 Nseirat section in Mauritania and Anti-Atlas section in Morocco, where post-glacial Hirnantian
681 chitinozoan assemblages have been documented, need to be investigated for acritarch and
682 miospore content, for possible extension of the reported earliest Rhuddanian species to the latest
683 Hirnantian.

684

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686

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701

702 **Appendix A. Supplementary data**

703 Supplementary data associated with this article can be found, in the online version, at xxx.

704

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896

897 **Tables**

898

899 Table 1. List of the main palynological and lithological data for the samples processed from well
900 JA-2 and the UN-REMSA well for chitinozoan analysis.

901

902 Table 2. Range and relative frequencies (counted number of species) of the acritarchs recorded
903 in the processed samples from well JA-2 and the UN-REMSA well.

904

905 Table 3. Range and relative frequencies (counted number of species) of the sporomorphs and
906 *Tortubus portuberans* recorded in the processed samples from well JA-2 and the UN-REMSA
907 well.

908
909 Table 4. Kerogen analysis data (grain count of all sizes undertaken under transmitted light) on
910 samples from well JA-2 and on cutting samples (SJS0001) from the UN-REMSA well. Numbers
911 are in percentages.

912
913 Table 5. Chitinozoan reflectance (R_{ch}) values in % of core samples from well JA-2 (provided by
914 John E. A. Marshall, University of Southampton). The measured reflectance values (average)
915 have been corrected against a standard which was measured at the start and end of every sample
916 series. For every sample the corrected value is close to the average value, showing that there has
917 been not much instrumental drift during reflectance measurements. The vitrinite reflectance (R_v)
918 values in % were calculated using the equation in Tricker et al. (1992).

919

920 **FIGURE CAPTIONS**

921

922 Fig. 1. Map of Libya showing surface outcrops with Paleozoic rocks (dark grey colour) and the
923 location of Jebel Asba at the eastern margin of the Kufra Basin (after Paris et al., 2012). The drill
924 site localities of well CDEG-2a in central Dor el Gussa (Paris et al., 2012) and well JA-2 in
925 southern Jebel Asba (this study) are indicated. The UN-REMSA well was found some 530 m
926 towards the NNE from JA-2 (not shown in the map).

927

928 Fig. 2. Lithological log of the core from well JA-2 together with biostratigraphic age,
929 chitinozoan abundance and kerogen analysis data (see also Table 4). See text for explanation

930

931 Fig. 3. Selected palynomorph species with stratigraphic ranges and regional occurrences in
932 North Africa, the Middle East and USA (Becip, 1974; Jardiné et al., 1974; Johnson, 1985;
933 Molyneux and Paris, 1985; Hill and Molyneux, 1988; Keegan et al., 1990; Le Hérissé et al.,
934 1995; Paris et al., 2012) and comparison with the present study.

935

936 Fig. 4. Range, relative frequencies and abundances of the chitinozoans recorded in the processed
937 samples from well JA-2.

938

939 Fig. 5. Correlation table for some Gondwana chitinozoan-bearing strata around the Ordovician-
940 Silurian boundary and their relative stratigraphical position with regard to the range of the main
941 diagnostic chitinozoan species, and to the standard graptolite biozones. 1: F. Paris, unpublished
942 data, 2: Grignani et al., 1991; 3: Paris et al., 2008; 4: Molyneux and Paris, 1985; 5: Paris, 1988;
943 6: Paris et al., 2012; 7: Le Hérissé et al., 2013; 8: Butcher, 2009; 9: Paris et al., 1998; 10:
944 Vandenbroucke et al., 2009; 11, Bourahrouh, 2002; 12: Piçarra et al., 2002; 13: Dufka and Fatka,
945 1993. Red line: exclusive Late Ordovician species; blue line: exclusive early Silurian taxa; black
946 line: taxa ranging possibly through the Ordovician–Silurian boundary. The blue stripe
947 corresponds to a brief but poorly constrained time slice of uppermost Hirnantian or lowermost
948 Rhuddanian age (i.e. “interregnum” between the top of the *persculptus* and the base of the
949 *ascensus* graptolite biozones; see discussion in Legrand, 2009).

950

951 **PLATES**

952

953 **Plate I.** Scale bar = 10 μm .

- 954 1: *Rugosphaera tuscarorensis* Strother & Traverse, 1979. Slide no. 5758-3. Core
955 sample at 57.58 m depth. England finder location: S34-1.
956 2: *Lophozonotriletes* sp. Slide no. 5758-3. Core sample at 57.58 m depth. England
957 finder location: S34-4.
958 3: *Tortotubus protuberans* Johnson, 1985. Slide no. 5758. Core sample at 57.58 m
959 depth. England finder location: L28.
960 4: *Ambitisporites dilutus* (Hoffmeister) Richardson & Lister, 1969. Slide no. 5553.
961 Core sample at 55.53 m depth. England finder location: T10.
962 5: *Dyadosphaera murusdensa* Strother & Traverse, 1979. Slide no. 5758. Core
963 sample at 57.58 m depth. England finder location: V37.
964 6: *Ambitisporites dilutus* (Hoffmeister) Richardson & Lister, 1969. Slide no. 6759.
965 Core sample at 67.59 m depth. England finder location: H45-2. Note: The slide
966 number corresponds to the core sample depth in cm.
967 7: *Ambitisporites dilutus* (Hoffmeister) Richardson & Lister, 1969. Slide no. 6782-5.
968 Core sample at 67.82 m depth. England finder location: L31-2.
969 8: *Tetraedraletes medinensis* Strother & Traverse, 1979, emend. Wellman and
970 Richardson, 1993. Slide no. 6782-5. Core sample at 67.82 m depth. England
971 finder location: K31-2.
972

973 **Plate II.** Scale bar = 10 μm .

- 974 1: *Rugosphaera tuscarorensis* Strother & Traverse, 1979. Slide no. 5758. Core
975 sample at 57.58 m depth. England finder location: J37-1.
976 2: *Dyadosphaera murusdensa* Strother & Traverse, 1979. Slide no. 5758. Core
977 sample at 57.58 m depth. England finder location: f41-2.
978 3: *Tetraedraletes medinensis* Strother & Traverse, 1979, emend. Wellman &
979 Richardson, 1993. Slide no. 5758. Core sample at 57.58 m depth. England finder
980 location: J29-2.
981 4: *Veryhachium lairdii* group (Deflandre) Deunff, 1954 ex Loeblich, 1970. Slide no.
982 6782-5. Core sample at 67.82 m depth. England finder location: W28.
983 5: *Archaeozonotriletes chulus* var. *chulus* (Cramer) Richardson & Lister, 1969.
984 Slide no. 6759. Core sample at 67.59 m depth. England finder location: J29-3.
985 6: *Dyadosphaera murusdensa* Strother & Traverse, 1979. Slide no. 6782. Core
986 sample at 67.82 m depth. England finder location: F21-1.
987 7: *Tasmanites* sp. Slide no. 4818. Core sample at 48.18 m depth. England finder
988 location: J41.
989 8: *Veryhachium lairdii* group (Deflandre) Deunff, 1954 ex Loeblich, 1970. Slide no.
990 6782-5. Core sample at 67.82 m depth. England finder location: X21-1.
991

992 **Plate III.** Scale bar = 10 μm .

- 993 1: *Leiosphaeridia* sp. Slide no. 5758-1. Core sample at 57.58 m depth. England
994 finder location: R44-3.
995 2: *Rugosphaera* sp. Slide no. 5758-2. Core sample at 57.58 m depth. England finder
996 location: T22.

- 997 3: *Leiosphaeridia acerscabrella* Johnson, 1985. Slide no. 6782-5. Core sample at
998 67.82 m depth. England finder location: T34-2.
- 999 4: *Leiosphaerida* sp. (in clusters). Slide no. 6782-5. Core sample at 67.82 m depth.
1000 England finder location: K32
- 1001 5: *Filisphaeridium* sp. Slide no. 6782-5. Core sample at 67.82 m depth. England
1002 finder location: H32-4.
- 1003 6: *Solisphaeridium* sp. Slide no. 6759. Core sample at 67.59 m depth. England
1004 finder location: W23-4.
- 1005 7: *Diexallophasis denticulata* (Stockmans & Williere) Loeblich, 1970. Slide no.
1006 6782. Core sample at 67.82 m depth. England finder location: V31-2.
- 1007 8: *Diexallophasis denticulata* (Stockmans & Williere) Loeblich, 1970. Slide no.
1008 6782-5. Core sample at 67.82 m depth. England finder location: F18-2.
- 1009

1010 **Plate IV.** Scale bar = 10 μ m.

- 1011 1: *Eupoikilofusa striatifera* Cramer, 1970. Slide no. 4818-4. Core sample at 48.18 m
1012 depth. England finder location: M19.
- 1013 2: *Eupoikilofusa striatifera* Cramer, 1970. Slide no. 5758-3. Core sample at 57.58 m
1014 depth. England finder location: W22.
- 1015 3: *Leiofusa estrecha* Cramer, 1964. Slide no. 6782-5. Core sample at 67.82 m depth.
1016 England finder location: H31-4.
- 1017 4: *Moyeria cabottii* (Cramer) Miller & Eames, 1982. Slide no. 6782-5. Core sample
1018 at 67.82 m depth. England finder location: K32-2.
- 1019 5: *Veryhachium trispinosum* (Eisenack) Stockmans & Williere, 1962. Slide no.
1020 4818-4. Core sample at 48.18 m depth. England finder location: V24
- 1021 6: *Geron* cf. *gracilis* Cramer, 1969. Note that the tail like feature characteristic in
1022 genus *Geron* is visible in phase contrast only. Slide no. 5758-1. Core sample at
1023 57.58 m depth. England finder location: D3-2.
- 1024 7: *Veryhachium trispinosum* (Eisenack) Stockmans & Williere, 1962. Slide no.
1025 5758-1. Core sample at 57.58 m depth. England finder location: W19-2.
- 1026 8: *Veryhachium europaeum* Stockmans & Williere, 1960, 1954 ex Loeblich, 1970.
1027 Slide no. 5758-2. Core sample at 57.58 m depth. England finder location: Q27-3.
- 1028

1029 **Plate V.** Scale bar = 10 μ m.

- 1030 1: *Micrhystridium* sp. (8 spined form). Slide no. 6721. Core sample at 67.21 m
1031 depth. England finder location: U23.
- 1032 2: *Veryhachium trispinosum* (Eisenack) Stockmans & Williere, 1962. Slide no.
1033 6721. Core sample at 67.21 m depth. England finder location: M13.
- 1034 3: *Veryhachium trispinosum* (Eisenack) Stockmans & Williere, 1962. Slide no.
1035 6782-5. Core sample at 67.82 m depth. England finder location: K26-2.
- 1036 4: *Veryhachium europaeum* Stockmans & Williere, 1960. Slide no. 6782-5. Core
1037 sample at 67.82 m depth. England finder location: G28-1.
- 1038 5: *Veryhachium trispinosum* (Eisenack) Stockmans & Williere, 1962. Slide no.
1039 6782-5. Sample at 67.82 m depth. England finder location: G33-3.
- 1040 6: *Veryhachium* sp. (4 spined). Slide no. 6782-5. Core sample at 67.82 m depth.
1041 England finder location: J24-4.
- 1042 7: *Micrhystridium* sp. (8 spined). Slide no. 6782-5. Core sample at 67.82 m depth.
1043 England finder location: K34-1.

1044 8: *Veryhachium lairdii* (Deflandre) Deunff, 1954 ex Loeblich, 1970. Slide no. 6782-
1045 5. Core sample at 67.82 m depth. England finder location: Q21.

1046

1047 **Plate VI.** Scale bar = 100 μm , except for 1b, 2b, 3b, 4b, 6b, 7b and 9b (10 μm).

1048 1a–b, 2a–b: *?Spinachitina verniersi* Vandenbroucke, in Vandenbroucke et al., 2009. Core
1049 sample at 55.53 m depth; IGR 72962. 1a (O49/3): conical specimen with gently
1050 tapering flanks and granules/spines concentrated on the margin. 1b: close-up of
1051 the granules/spines (less than 2 microns length, but possibly eroded) concentrated
1052 on the margin. Some granules seem also scattered on the chamber. 2a (N44/4):
1053 flattened specimen (vesicle of 150 μm length) with a tilted bottom. 2b: close-up
1054 of the spines (up to 2 μm length) erected on the margin (not exactly arranged in a
1055 single row).

1056 3a–b: *Spinachitina verniersi* Vandenbroucke, in Vandenbroucke et al., 2009. Core
1057 sample at 55.53 m depth; IGR 72962 (L47/4). 3a: conical vesicle showing the
1058 diagnostic crown of densely distributed spines/granules on the margin. 3b: detail
1059 of the spines/granules (up to 3 μm length) forming a crown around the carina.

1060 4a–b, 8a–b: *Euconochitina moussegoudaensis* Paris, in Le Hérissé et al., 2013. Core sample at
1061 67.82 m depth; IGR 72987. 4a (O47/2): conical specimen with gently tapering
1062 flanks and a slightly flaring collarette. 4b: close-up of the smooth wall surface. 8a
1063 (O47/3): specimen (vesicle of 146 μm length) with a partly tilted bottom. 8b:
1064 close-up of the margin devoid of spines or granules.

1065 5: *Plectochitina cf. longispina* (Achab, 1978). Core sample at 67.82 m depth; 72987
1066 (L38/3).

1067 6a–b: *?Spinachitina verniersi* Vandenbroucke, in Vandenbroucke et al., 2009. Core
1068 sample at 60.23 m depth; IGR 729864 (O47). 6a (O47/2): conical specimen with
1069 gently tapering flanks. 6b: close-up of the margin showing possible granules in
1070 row.

1071 7a–b: *?Spinachitina verniersi* Vandenbroucke, in Vandenbroucke et al., 2009. Core
1072 sample at 67.82 m depth; IGR 72987 (L43/1). 7a: long conical specimen with a
1073 gently flaring collarette and spines concentrated on the margin. 7b: close-up
1074 showing the spines (up to 3 μm length) concentrated on the margin. Some
1075 granules (less than 1 μm length) seem also scattered on the lower part of the
1076 chamber.

1077 9: *Plectochitina* sp. Core sample at 60.23 m depth; IGR 72964 (N45/1). Note the
1078 long processes branched at their distal part (most of them are broken). The neck is
1079 likely damaged.

1080 10: *Plectochitina cf. longispina* (Achab, 1978). Core sample at 67.82 m depth; IGR
1081 72987 (M46). Specimen with a long neck ended by a flaring collarette. The
1082 processes branch at their about 2/3 of their length.

1083

1084 **Plate VII.** Scale bar = 100 μm , except for 1b, 1c, 2b, 3b, 4b, 9b and 9c (10 μm).

1085 1a–c, 3a–b, 4a–b, 6, 8, 9a–c: *Spinachitina oulebsiri* Paris et al., 2000. Core sample at 67.59 m
1086 depth; IGR 72981. 1a (M44/1): typical specimen with a well-developed crown of
1087 spines (about 20 spines) erected around its margin. 1b: close-up of the spines (up
1088 to 8 μm length) showing their slender conical shape and their widened hollow
1089 base. 1c: detail of the wall surface, which seems rough at high magnification
1090 (possibly covered by a bacterial mat). 3a (Q47/1): fairly long specimen (vesicle of

- 1091 170 µm length) with a well-developed crown of spines (about 24 spines) around
 1092 its margin and a conspicuous supra-margin constriction. 3b: close-up of the spines
 1093 (up to 8 µm length) erected on the margin showing their slender conical shape and
 1094 their widened hollow base. 4a (L48): long specimen (vesicle of 190 µm length)
 1095 with a well-developed crown of spines (about 20 spines) around its margin. The
 1096 supra-margin constriction is weak. 4b: close-up of the slender conical spines (up
 1097 to 11 µm length); note the bi-rooted base (possibly resulting of the collapse of the
 1098 wall of the hollow base). 6 (L48/4): short conical vesicle (vesicle of 130 µm
 1099 length). 8 (O49): very short vesicle (close to 100 µm), note the serrated aperture.
 1100 9a (Q49/4): unusual long vesicle (length close to 300 µm) with a conspicuous
 1101 supra-margin constriction and a fenestrate aperture. 9b: close-up of the crown of
 1102 densely distributed spines (about 30). 9c: close-up of the fenestrate aperture.
 1103 2a–b: *Spinachitina verniersi* Vandenbroucke, in Vandenbroucke et al., 2009. Core
 1104 sample at 67.59 m depth; IGR 72981 (Q47). 2a: conical vesicle showing the
 1105 diagnostic crown of densely distributed granules on the margin. 2b: detail of the
 1106 granules arranged in a crown on the carina.
 1107 5: *Euconochitina moussegoudaensis* Paris, in Le Hérisse et al., 2013. Core sample at
 1108 67.59 m depth; IGR 72981 (P47/3).
 1109 7. ?*Spinachitina verniersi* Vandenbroucke, in Vandenbroucke et al., 2009. Core
 1110 sample at 67.59 m depth; IGR 72981 (N49/3). Vesicle with granules concentrated
 1111 on the margin. However, they are not clearly arranged in crown.
 1112
 1113 **Plate VIII.** Chitinozoans and one scolecodont from cuttings (no depth provided) from the UN-
 1114 REMSA well, Kufra Basin, Libya; IGR 72995. Scale bar = 100 µm, except for
 1115 3b, 5b, 6b, 8, 9b, 10b (10 µm) and 6c (1 µm).
 1116 1: *Cyathochitina caputoi* Da Costa, 1971. (Q44); note the thick carina and the
 1117 longitudinal ridges at the junction of the chamber and of the neck.
 1118 2: Scolecodont partly “coated” with amorphous organic matter (R45/4).
 1119 3a–b, 4, 5a–b: *Euconochitina moussegoudaensis* Paris, in Le Hérisse et al., 2013. 3a (S46):
 1120 slightly conical specimen with a well-developed cylindrical neck. 3b: close-up of
 1121 the margin devoid of spines. The granules (about 1 µm) represent likely organic
 1122 particles stuck on the margin. 4 (U48): gently tapering conical vesicle without any
 1123 ornamentation on its margin. 5a (S48): slender conical specimen (vesicle of 161
 1124 µm length). 5b: close-up of the margin showing minute granules (less than one
 1125 µm) concentrated around the base.
 1126 6a–c, 9a–b, 10a–b: *Spinachitina verniersi* Vandenbroucke, in Vandenbroucke et al., 2009.
 1127 6a (P45/2): conical vesicle showing the diagnostic crown of densely distributed
 1128 granules on the margin. 6b: detail of the crown of granules. 6c: close-up of the
 1129 granules more or less in row on the margin. 9a (O48/1): long conical vesicle (190
 1130 µm length). 9b: detail of the crown of eroded granules. 10a (P49/3): conical
 1131 vesicle (161 µm length) with densely distributed granules more or less forming a
 1132 crown on the margin. 10b: detail of the crown of granules on the margin;
 1133 additional minute granules are randomly scattered on the lower part of the
 1134 chamber.
 1135 7–8: Ancyrochitiniinae indet. 7 (N44): damaged vesicle (broken processes) coated with
 1136 amorphous organic matter. 8 (L47/4): antiapertural view of a specimen with
 1137 broken processes.

- 1138
- 1139 **Plate IX.** Scale bar = 100 μm , except for 4, 7, 8 (10 μm) and 3, 5 and 10 (1 μm).
- 1140 1, 6–8: *Tortotubus protuberans* Johnson, 1985. 1: Core sample at 60.23 m depth; IGR
- 1141 72964 (O43); long branched structure. 6: Core sample at 67.59 m depth; IGR
- 1142 72981 (P45/3); fragment of branched structure. 7: Close up of fig. 6 showing
- 1143 bulb-like “vesicles” at the junction between the four branches. 8: Close up
- 1144 showing detail of the bulb-like “vesicles” protruding on the surface of the longest
- 1145 branch of fig. 6.
- 1146 2–5: Amorphous organic matter (biofilm) after oxidation with HNO_3 . Core sample at
- 1147 67.40 m depth; IGR 72979. 2: Large fragment of organic “sheet”. 3: Tilted view
- 1148 of the “sheet” showing the spongy structure of the section. 4: Fragment of
- 1149 “sheet”; see the straight border of a few μm thick. 5: Casts of framboids of pyrite
- 1150 after dissolution with HNO_3 .
- 1151 9: Chitinozoan specimen (Ancyrochitininae) adhesively associated with amorphous
- 1152 organic matter (biofilm). Core sample at 67.82 m depth; IGR 72987 (K43/2).
- 1153 10: “Sheets” of amorphous organic matter (biofilm). Core sample at 67.82 m depth,
- 1154 IGR 72987. Detail of the cast of framboids of pyrite when dissolved with HNO_3 .
- 1155
- 1156 **Plate X.** Scale bar = 100 μm , except for 13 and 21b (50 μm).
- 1157 1: *Euconochitina moussegoudaensis* Paris, in Le Hérissé et al., 2013. Core sample at
- 1158 46.60 m depth; IGR 72954 (L48). Short thickset specimen.
- 1159 2: *Euconochitina* cf. *moussegoudaensis* Paris, in Le Hérissé et al., 2013. Core
- 1160 sample at 46.60 m depth; IGR 72954 (H40). Elongate and slender specimen
- 1161 showing a supra-margin constriction.
- 1162 3: *Euconochitina* cf. *moussegoudaensis* Paris, in Le Hérissé et al., 2013. Core
- 1163 sample at 48.18 m depth; IGR 72957 (H50/1). Very long specimen.
- 1164 4: ?*Euconochitina moussegoudaensis* Paris, in Le Hérissé et al., 2013. Core sample
- 1165 at 50.73 m depth; IGR 72962 (M46). Teratological specimen with a sleeve
- 1166 gaining the lower vesicle and extending around the succeeding one .
- 1167 5: *Euconochitina moussegoudaensis* Paris, in Le Hérissé et al., 2013. Core sample at
- 1168 50.73 m depth; IGR 72958 (R40/3).
- 1169 6: *Euconochitina moussegoudaensis* Paris, in Le Hérissé et al., 2013. Core sample at
- 1170 55.07 m depth; IGR 72959 (S36).
- 1171 7: *Euconochitina moussegoudaensis* Paris, in Le Hérissé et al., 2013. Core sample at
- 1172 60.23 m depth; IGR 72965 (M39/1). Short specimen.
- 1173 8, 10: *Euconochitina moussegoudaensis* Paris, in Le Hérissé et al., 2013. Core sample at
- 1174 64.02 m depth; IGR 72967. 8 (G32/4). 10: short specimen (G41/2).
- 1175 9: *Euconochitina* cf. *moussegoudaensis* Paris, in Le Hérissé et al., 2013. Core
- 1176 sample at 64.02 m depth; IGR 72967 (G38/4). Elongate and slender specimen
- 1177 with a supra-margin constriction.
- 1178 11: *Euconochitina* cf. *moussegoudaensis* Paris, in Le Hérissé et al., 2013. Core
- 1179 sample at 65.74 m depth; IGR 72968 (O42). Elongate and slender specimen with
- 1180 a supra-margin constriction.
- 1181 12: *Euconochitina moussegoudaensis* Paris, in Le Hérissé et al., 2013. Core sample at
- 1182 65.74 m depth; IGR 72968 (P43/3). Short and thickset specimen.
- 1183 13: *Calpichitina* sp. Core sample at 66.85 m depth; IGR 72970 (J50/2).

- 1184 14–16: *Euconochitina moussegoudaensis* Paris, in Le Hérisse et al., 2013. Core sample at
 1185 66.85 m depth. 14: (N39); 15: (L45); 16 (T34/4).
 1186 17: Ancyrochitinidae indet. Core sample at 67.05 m depth (H44).
 1187 18: *Euconochitina moussegoudaensis* Paris, in Le Hérisse et al., 2013. Core sample at
 1188 67.05 m depth. Short and thickset specimen (Q41/1).
 1189 19–20: *Euconochitina* cf. *moussegoudaensis* Paris, in Le Hérisse et al., 2013. Core
 1190 sample at 67.05 m depth; IGR 72974. Elongate and slender specimens with a
 1191 weakly expressed supra-margin constriction. 19 (Q42); 20 (K49/1).
 1192 21a–b: *Spinachitina* cf. *S. oulebsiri* Paris et al., 2000. Core sample at 62.34 m depth; IGR
 1193 72966 (F.35/4); 21b: close-up showing the spines on the margin.

1194
 1195 **Plate XI.** Scale bar = 100 µm.

- 1196 1: *Spinachitina oulebsiri* Paris et al., 2000. Core sample at 67.21 m depth; IGR
 1197 72975 (F37/4).
 1198 2: *Spinachitina* cf. *verniersi* Vandenbroucke, in Vandenbroucke et al., 2009. Core
 1199 sample at 67.21 m depth; IGR 72975 (M45). Specimen showing a conspicuous
 1200 supra-margin constriction.
 1201 3: *Euconochitina* cf. *moussegoudaensis* Paris, in Le Hérisse et al., 2013. Core
 1202 sample at 67.21 m depth; IGR 72975 (N47/2).
 1203 4: *Spinachitina* cf. *verniersi* Vandenbroucke, in Vandenbroucke et al., 2009. Core
 1204 sample at 67.40 m depth; IGR 72976 (M38/2). Short specimen.
 1205 5: *Euconochitina* cf. *moussegoudaensis* Paris, in Le Hérisse et al., 2013. Core
 1206 sample at 67.40 m depth; IGR 72976 (035).
 1207 6: *Spinachitina oulebsiri* Paris et al., 2000. Core sample at 67.59 m depth; 72982
 1208 (L52). Abnormally short specimen.
 1209 7–10: *Spinachitina oulebsiri* Paris et al., 2000. Core sample at 67.59 m depth; 72982. 7:
 1210 short specimen (M45). 8: (O36). 9: slender specimen (V49). 10: (O47)
 1211 11: *Euconochitina* cf. *moussegoudaensis* Paris, in Le Hérisse et al., 2013. Core
 1212 sample at 67.82 m depth; 72982 (K44/2). Elongate and slender specimen with a
 1213 supra-margin constriction and a uncommon well-developed neck.
 1214 12: *Euconochitina* sp. aff. *vitrea* (Taugourdeau, 1962). Core sample at 67.82 m depth;
 1215 IGR 72985 (K40/1).
 1216 13–15, 17: *Plectochitina* cf. *longispina* (Achab, 1978). Core sample at 67.82 m depth; IGR
 1217 72985. 13: well-developed neck and broken processes (L48/4). 14: long branched
 1218 processes (R34/3). 15: note the spongy processes (K46/1). 17: specimen with
 1219 well-branched processes stuck on a biofilm (S37/4).
 1220 16: *Euconochitina moussegoudaensis* Paris, in Le Hérisse et al., 2013. Core sample at
 1221 67.97 m depth; IGR 72988 (O44/3).
 1222 18–20: *Euconochitina moussegoudaensis* Paris, in Le Hérisse et al., 2013. Cuttings from
 1223 UN-REMSA well; IGR 72955 18: (L43/2); 19: (O37/3); 20: (P39/4).
 1224 21: *Cyathochitina caputoi* Da Costa, 1971. Cuttings from UN-REMSA well; IGR
 1225 72995 (K38).

1226
 1227 **Plate XII.** Scale bar = 100 µm, except for 7, 8, 10–13 and 19 (50 µm).

- 1228 1–2, 17: Scolecodont indet. 1: Core sample at 46.60 m depth; IGR 72954 (O43/3). 2: Core
 1229 sample at 48.18 m depth; IGR 72957 (U42). 17: Core sample at 67.21 m depth;
 1230 IGR 729575 (M39/3).

- 1231 3–6: Eurypterid remains. Core sample at 50.73 m depth; IGR 72958. 3: fragment of
1232 cuticle (M41/1). 4: fragment of cuticle of a ventral segment (P44/1). 5: “sensorial
1233 hair” (P34/1). 6: claw? (M41/1).
- 1234 7: Ornamented palynomorph recalling *Tasmanites tzadiensis* La Hérisse, in Le
1235 Hérisse et al., 2013. Core sample at 50.73 m depth; IGR 72958 (S34).
- 1236 8, 11–13: *Tasmanites tzadiensis* Le Hérisse, in Le Hérisse et al., 2013. 7: Core sample at
1237 50.73 m depth (S34). 8: Core sample at 50.73 m depth (Q42/3). 11: Core sample
1238 at 60.23 m depth (J28/1). 12: Core sample at 62.34 m depth (M39). 13: Core
1239 sample at 66.85 m depth (L47/1).
- 1240 9, 14, 18: *Tortotubus protuberans* Johnson, 1985. 9: Core sample at 57.58 m depth; IGR
1241 72963 (M51); branched structure. 14: Core sample at 66.85 m depth; IGR 72970
1242 (U48/1); fragment. 18: Core sample at 67.21 m depth; IGR 72975 (S43);
1243 branched element.
- 1244 10: Connected palynomorphs. Core sample at 57.58 m depth; IGR 72963 (N47/4).
- 1245 15–16: “Sheets or blades” of amorphous organic matter (biofilm). Core sample at 66.85
1246 m depth. 15: framboids of pyrite removed (circular depressions) after oxidation
1247 with HNO₃. IGR 72973 (N39/2). 16: biofilm without oxidation by HNO₃ showing
1248 black microspheres representing framboids of pyrite; IGR 72972 (P45/1).
- 1249 19: ?Colony of cyanobacteria. Core sample at 67.97 m depth; IGR 72988 (R50/2).

Figure 1

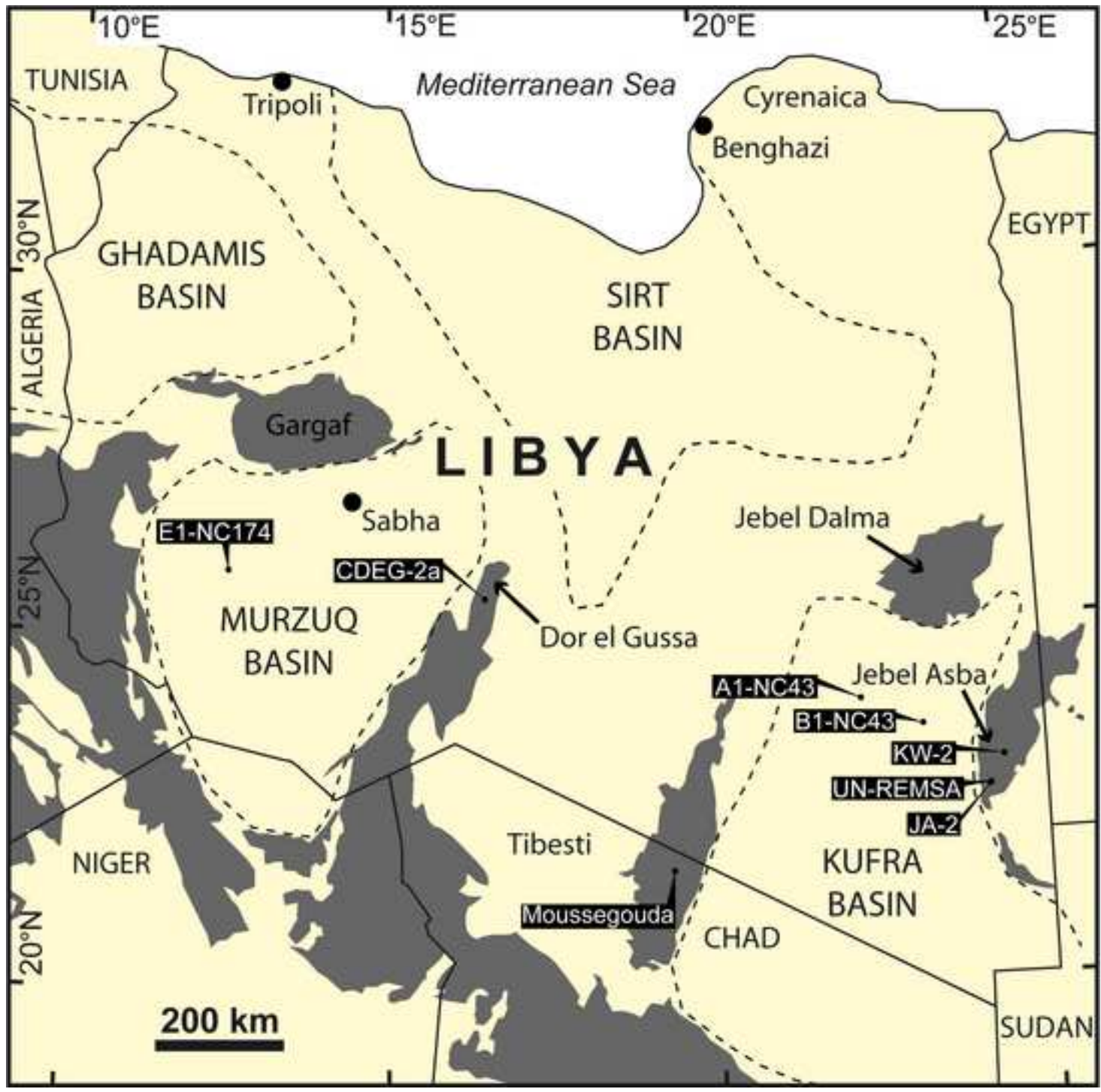


Figure 2

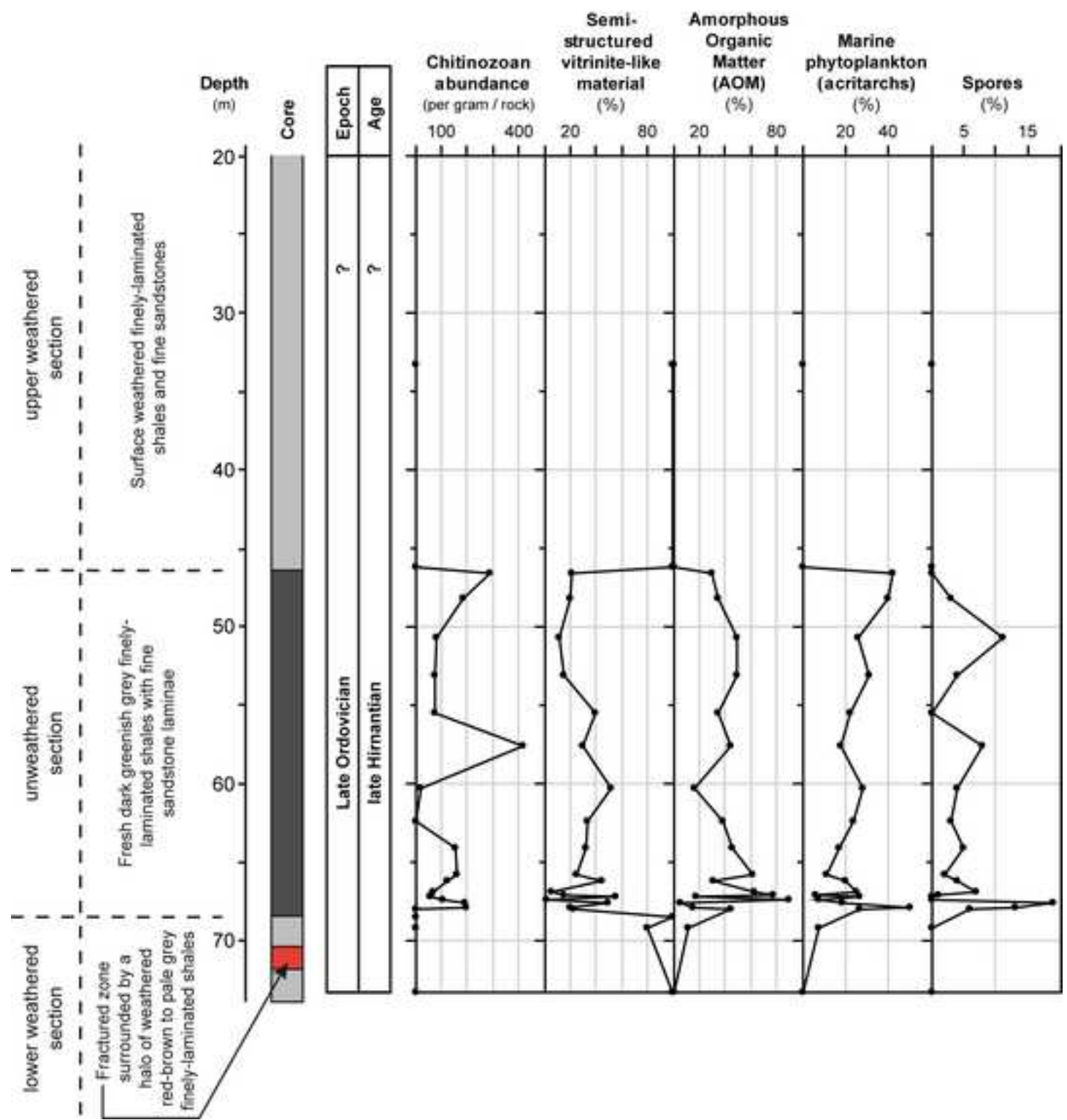


Figure 3

Caradocian	Ordovician		AGE	SELECTED SPECIES
	Ashgillian	Silurian		
			1. <i>Eupoikilofusa striatifera</i>	
			2. <i>Veryhachium trispinosum</i>	
			3. <i>Dixallopthisis denticulata</i>	
			4. <i>Leiosphaeridia acerscrabrella</i>	
			5. <i>Moyeria cabottii</i>	
			6. <i>Veryhachium europaeum</i>	
			7. <i>Leiofusa estrecha</i>	
			8. <i>Tunisphaeridium</i> sp.	
			9. <i>Geron</i> cf. <i>gracilis</i>	
			10. <i>Filisphaeridium</i> sp.	
			11. <i>Buedingilispaeridium</i> sp.	
			12. <i>Tetraedraletes medienensis</i>	
			13. <i>Ambitisporites dilutus</i>	
			14. <i>Archaeozonitoides chulus</i> var. <i>chulus</i>	
			15. <i>Tortotubus protuberans</i>	
			16. <i>Rugosphaera tuscarorensis</i>	
			17. <i>Dyadosphaera murusdensa</i>	
			No previous record from Silurian	KUFRA
		1, 2, 3, 6, 7, 11, 12, 17	Paris et al. (2012)	MURZUQ
		1, 2, 3, 7, 9, 12, 14, 17	Beccip (1974) and unpublished data	GHADAMIS
		1, 2, 3, 9, 10, 11, 12, 13, 17	Molyneux and Paris (1985); Hill and Molyneux (1988)	NE LIBYA
		Zone LL1-LL2		
		1, 2, 3, 7	Jardiné et al. (1974)	ALGERIA
		Zone G1-G2		
			No previous record from Silurian	MOROCCO
		1, 3, 5, 8, 9, 10, 11	Le Hérisse et al. (1995)	SAUDI ARABIA
		Zone 2-3		
		9, 13, 14, 17	Keegan et al. (1990)	JORDAN
		Zone JS-3		
		4, 12, 13, 15, 16	Johnson (1985)	USA
				PENNSYLVANIA

Figure 4

JA-2 (depth in m)	<i>Euc. moussegoudaensis</i>	<i>E. cf. moussegoudaensis</i>	<i>Euconochitina</i> sp.	<i>Plectochitina</i> sp.	<i>Spinachitina</i> sp.	<i>Eucono. sp. aff. vitrea</i>	<i>Spinachitina vermiersi</i>	<i>Calpichitina</i> sp.	<i>Ancyrochitininae</i> indet.	<i>Spinachitina oulebsiri</i>	<i>Plecto cf. longispina</i>	<i>Belonechitina</i> sp.	<i>Conochitinidae</i> indet.	Chitinozoan abundance per gam / rock
33.33	100													<1
46.20	100													<1
46.60	98	<1	<1											292
48.18	98	<1	<1	<1										189
50.73	98		2											82
53.07	99		<1											74
55.53	99						<1							75
57.58	98	<1	<1											415
60.23	98						?				<1			23
62.34	96				3					cf.				5
64.02	95	1	4											128
65.74	96	2				<1	<1							160
66.21	99		<1											157
66.85	98		<1					<1						72
67.05	96	2							<1	cf.				61
67.21	96	<1					cf.		1	2				59
67.40	96						2			2				109
67.59	44	<1					20		<1	35				190
67.82	26	<1		<1		<1	?				70	<1		197
67.97	85			15										3
68.42														/
69.12	100													<1
73.21													100	<1

Table 1

Table 1.

Sample depth (m)	Available sample (g)	Processed sample (g)	SEM observation	Chitinozoan abundance per gram / rock	Sorted %	Biofilm	Scolecodonts	Eurypterids	Tasmanites	Lithology	Traces of weathering
JA-2											
33.33	10.4	4.0		<1	100	X				beige silty shale	XX
46.20	10.9	5.6		<1	100	X	X			beige silty shale	X
46.60	10.2	5.0	YES	292	10	X	X		X	grey silty shale	
48.18	11.3	5.6		189	62		X			grey silty shale	
50.73	9.3	4.3		82	90		X	X	X	grey silty shale	
53.07	6.7	4.0		74	50	XX				grey silty shale	
55.53	14.3	6.0	YES	75	100					grey shale	
57.58	11.6	5.1		415	10					grey siltst., micas	
60.23	7.1	5.1	YES	23	100			X	X	grey siltst., micas	
62.34	8.5	5.1		5	100			X	X	grey siltst., micas	
64.02	11.3	7.0		154	10	X		X		grey siltstone	
65.74	7.7	5.0		160	10	X				grey shale	
66.21	14.5	7.0		128	10	XX				grey shale	
66.85	10.0	5.1		72	20	XX			X	grey shale	
67.05	5.0	3.5		61	80	XX				greenish shale	
67.21	5.6	3.7		59	90	XX	X			greenish shale	
67.40	4.6	3.3	YES	109	80	XX				greenish shale	
67.59	8.0	5.0	YES	190	10	X				grey shale	
67.82	4.4	3.2	YES	197	50	XX				fine beige sand.	
67.97	3.8	2.4		3	100				X	fine beige sand.	X
68.42	5.2	3.2		/	100					fine beige sand.	X
69.12	8.6	5.2		<1	100	X				whitish	XX
73.21	11.3	5.0		<1	100	X				grey shale	
UN-REMSA											
SJS0001		4.0	YES	125	10	X	X			dark silty shale	

Explanation: X (present), XX (abundant)

Table 2.

Sample depth (m)	<i>Leiosphaeridia</i> spp.	<i>Solisphaeridium</i> spp.	<i>Eupoikilofusa striatifera</i>	<i>Tasmanites</i> spp.	<i>Veryhachium trispinosum</i>	<i>Veryhachium trispinosum (large)</i>	<i>Leiosphaeridia</i> spp. (clusters of small)	<i>Veryhachium</i> sp. (4 spined)	<i>Dictyotidium</i> spp.	<i>Leiosphaeridia</i> spp. clusters	<i>Diexallophasis denticulata</i>	<i>Geron</i> cf. <i>gracilis</i>	<i>Leiofusa</i> sp.	<i>Multiplicisphaeridium</i> spp.	<i>Veryhachium europaeum</i>	<i>Veryhachium lairdii</i>	<i>Filisphaeridium</i> sp.	<i>Micrhystridium</i> sp. (8 spined)	<i>Diexallophasis</i> spp.	<i>Leiosphaeridia</i> spp. (small)	<i>Veryhachium</i> sp. cluster	<i>Cymatiosphaera</i> spp.	<i>Tunisphaeridium</i> spp.	<i>Goniosphaeridium</i> spp.	<i>Leiosphaera small</i>	<i>Buedingisphaeridium</i> sp.	<i>Leiofusa estrecha</i>	<i>Leiosphaeridia acerscarbrella</i>	<i>Moyeria cabottii</i>	<i>Veryhachium trispinosum (globular form)</i>		
JA-2																																
33.33																																
46.20																																
46.60	C	R																														
48.18	C		R	R	R	R																										
50.73	C		C				R	R																								
53.07	C		R		R		R		C	R																						
55.53	A		R	R						R																						
57.58	C		R		R		R				R	R	R	R	R	R																
60.23	C				R		R						R	R	R	R																
62.34	C		R	R			C				R		R																			
64.02	C												R					R	A	R												
65.74	C		R		R		R																									
66.21	A						R					R	R	R				R				R										
66.85	A		R	R	R		R	R										R														
67.05	C		R											C									C									
67.21	A		R		R						R			C								R										
67.40	A		R																													
67.59	A	R	R	R	C		R	R					R											R	C							
67.82	A		R				R	R	C	C			R	C	R	R								R		R	R	R	R	R		
67.97	A							R							R																	
68.42																														R		
69.12																																
73.21																																
UN-REMSA																																
SJS0001	A		C																													

Explanation: R: Rare (1–5), C: Common (6–19), A: Abundant (20+)

Table 3.

Sample depth (m)	<i>Ambisporites dilutus</i>	<i>Ambisporites</i> spp.	<i>Dyadospora murusdensa</i>	Tetrad clusters	Tetrad indet.	Trilete spores	Verrucate spores	<i>Archaeozonotriletes</i> spp.	<i>Tetraedraletes medinensis</i>	<i>Archaeozonotriletes chulus</i> var. <i>chulus</i>	<i>Lophozonotriletes</i> spp.	<i>Tetraedraletes medinensis</i>	Reticulate spores	<i>Rugosphaera tuscarorensis</i>	<i>Tortotubus protuberans</i>
JA-2															
33.33															
46.20															
46.60	R	R	R	R	C	R	C								
48.18		R	C		A	R									
50.73		R	R		A	R	R	R							R
53.07		R	C		C	R			R						R
55.53	R		R		R	R		R	R						R
57.58	R		R		A		R		R	R	R	R	R	R	R
60.23		R			C										
62.34		R			A				R						R
64.02	R	R			C	R			R						R
65.74					C		R								C
66.21			R		C	R			R						
66.85					C				R					R	R
67.05			C		R				R						
67.21			C		C				R					R	
67.40			C		C			R	R						
67.59	C	R	R		A	C			R	R					R
67.82	C		R		A	C			R						R
67.97	R					A			R		R				R
68.42		R	C			C				R					R
69.12															
73.21															
UN-REMSA															
SJS0001	R				A										R

Explanation: R: Rare (1–5), C: Common (6–19), A: Abundant (20+)

Table 4.

Sample depth (m)	Vitrinite –like, semistructered	Amorphous organic matter	Cutinite	Acritarchs	Inertinite	Vitrinite-like, degraded	Exinite spores	Exinite resinite	Exinite <i>Tasmanites</i>	Intertinite semifusinite
JA-2										
33.33	100									
46.20	100									
46.60	21	30	1	42	1	4				
48.18	20	35		40	1	1	3			
50.73	12	50		26	1		11			
53.07	15	50		31			4			
55.53	40	35		22				3		
57.58	30	44		18			8			
60.23	52	16		28			4			
62.34	34	38		24			3			
64.02	32	46		17			5			
65.74	25	61		11	1		2			
66.21	45	31		20			4			
66.85	5	63		25			7			
67.05	15	78		6			1			
67.21	55	18		27						
67.40	2	90		8						
67.59	50	6		19	6		19			
67.82	20	15		50		1	13	1		
67.97	22	45		27			6			
68.42	100									
69.12	80	11		8						1
73.21	100									
UN-REMSA										
SJS0001	5	89		2		2	2			

Table 5.

Sample depth (m)	R_{ch} average	Corrected average	Count	Standard deviation	Minimum	Maximum	R_v calculated
46.60	0.59	0.57	49	0.029	0.54	0.65	0.44
46.60	0.56	0.55	66	0.036	0.48	0.63	0.41
48.18	0.60	0.58	4	0.021	0.58	0.62	0.45
57.58	0.55	0.56	72	0.043	0.47	0.63	0.41
64.02	0.63	0.63	20	0.031	0.58	0.68	0.48
64.02	0.63	0.61	22	0.065	0.55	0.74	0.48
65.74	0.50	0.49	74	0.031	0.45	0.55	0.36
65.74	0.54	0.53	22	0.019	0.52	0.57	0.40
67.82	0.52	0.51	5	0.026	0.49	0.55	0.38

