



# **Latest Ordovician-earliest Silurian acritarchs and chitinozoans from subsurface samples in Jebel Asba, Kufra Basin, SE Libya**

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

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## Abstract

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

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

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

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

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

## **Research highlights**

- We describe palynomorphs from subsurface shales of SE Libya.
- The shales are of latest Hirnantian–earliest Rhuddanian age.
- The shales are immature for oil generation.
- Dominant chitinozoan species *Euconochitina moussegoudaensis* Paris.
- Discussion of the Ordovician–Silurian boundary.

## **1. Introduction**

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

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

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

## **2. Material and methods**

### *2.1. Sampling*

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

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

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

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

## 2.2. Sample preparation

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

### **3. Palynological results**

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

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

##### *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 *Tunisphaeridium* 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).



One of the peculiar characteristics of the palynological residues of JA-2 is the occurrence of large “blades” or “sheets” (up to 1 mm thick) of amorphous organic matter (Plate IX, 2–5, 10; Plate XII, 15–16). The chitinozoans and other palynomorphs are often adhesively associated with amorphous organic matter (Plate IX, 9; Plate XI, 14–15, 17) as result of which the processes of the Ancyrochitinae break frequently during sorting of the vesicles. These organic sheets are composed of agglomerated minute particles of several  $\mu\text{m}$  in length and less than one  $\mu\text{m}$  thick (Plate IX, 3 and 10). Pyrite framboids with 10  $\mu\text{m}$  in diameter are recorded, with the exception of a sole specimen of about 500 nm. Under transmitted light microscope, they appear as tiny black spheres in the brownish to yellowish organic sheets. After oxidation with  $\text{HNO}_3$ , the pyrite is dissolved and the casts of the framboids are visible (Plate IX, 5 and 10). The organic sheets are here called “biofilms”, produced by algae or by bacteria. The organic matter in the northern Gondwana “hot shale” has a similar structure with minute “flakes” of organic particles adhesively clumped with the organic-walled microfossils. However, in the JA-2 well samples, the AOM is concentrated in films coating the bedding plane, whereas in the classical “hot shale” this organic matter is a major component of the sediment (up to 30% in some cases). This organic matter may represent remnants of algae.

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

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

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

### 3.2. Chitinozoan assemblages

#### 3.2.1. Species from well JA-2

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

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

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

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

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

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

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

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

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

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

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

### 3.2.2. Species from the UN-REMSA well

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

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

### 3.3. Kerogen analysis and thermal maturity

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

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

## 4. Biostratigraphy, palaeoecology and regional correlation

### 4.1. Marine phytoplankton and land-derived plant element assemblages

The acritarchs assemblage is dominated by thin-walled *Leiosphaeridia* spp. often in clusters. Dorning (1981) found dominance of thin-walled leiosphaerids in the shallow marine Silurian (Ludlovian) sequence of the Welsh Borderland. The presence of land-derived vitrinite-like macerals and miospores–cryptospores is also indicative of a marginal marine (nearshore) depositional environment for the entire sequence of the studied well JA-2, although the interval 33.33–60.23 m does seem much closer to land with the dominance of land-derived plant remains.

In the late Silurian of the Ghadamis Basin, Al-Ameri (1983) erected six distinct types of palynofacies of which four contained acritarchs indicating increasing distance from the shoreline. Hill and Molyneux (1988) recognised two Llandoveryian palynofacies assemblages in NE Libya. Their southern assemblage located in southern Cyrenaica, north of the present study area, was also dominated by leiosphaerids. Hill and Molyneux (1988) consider their acritarch assemblage comparable most closely to Palynofacies 3 of Al-Ameri (1983), which is interpreted as inner neritic.

The studied assemblage is also comparable to the land-derived palynoflora (miospores–cryptospores and organic structures) of early Silurian (Rhuddanian) age from the Tuscarora Formation in central Pennsylvania, USA (Johnson, 1985). Based on these comparisons the present assemblage was probably deposited closer to the shoreline.

#### *4.1.1. Libya*

Acritarch assemblages recorded in well JA-2 are similar to those from other basins in North Africa, the Middle East, and North America (Fig. 3).



365

366 Kufra Basin

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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*, *Dyadospora murusdensa* and

380 *Tetrahedraletes 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*, *Tetrahedraletes 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.

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

#### 4.1.3. Algeria

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

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

#### 4.3. Ordovician–Silurian boundary

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

#### 4.4. Chronostratigraphical calibration of the Hirnantian and Rhuddanian chitinozoan biozones

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

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

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



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

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

Because the durations of the related glacial events are significantly shorter (ca. 10 ky) than the range of the recorded chitinozoan species (ca. 1 Ma or more), the Hirnantian glacial climax can be regarded as isochronous at the scale of the northern Gondwana chitinozoan 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

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

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

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

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

## 5. Conclusions

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

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

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

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

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## **Appendix A. Supplementary data**

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

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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

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

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

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

## FIGURE CAPTIONS

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



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

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

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

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

## 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: *Tetrahedraletes 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: *Tetrahedraletes 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  $\mu$ 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  $\mu$ 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.

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

**Plate VI.** Scale bar = 100  $\mu\text{m}$ , except for 1b, 2b, 3b, 4b, 6b, 7b and 9b (10  $\mu\text{m}$ ).

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

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

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

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

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

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

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

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

**Plate VII.** Scale bar = 100  $\mu\text{m}$ , except for 1b, 1c, 2b, 3b, 4b, 9b and 9c (10  $\mu\text{m}$ ).

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

- 1091 170  $\mu\text{m}$  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  $\mu\text{m}$  length) erected on the margin showing their slender conical shape and  
 1094 their widened hollow base. 4a (L48): long specimen (vesicle of 190  $\mu\text{m}$  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  $\mu\text{m}$  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  $\mu\text{m}$   
 1099 length). 8 (O49): very short vesicle (close to 100  $\mu\text{m}$ ), note the serrated aperture.  
 1100 9a (Q49/4): unusual long vesicle (length close to 300  $\mu\text{m}$ ) 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 Hérissé 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  $\mu\text{m}$ , except for  
 1115 3b, 5b, 6b, 8, 9b, 10b (10  $\mu\text{m}$ ) and 6c (1  $\mu\text{m}$ ).  
 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 Hérissé 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  $\mu\text{m}$ ) 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  $\mu\text{m}$  length). 5b: close-up of the margin showing minute granules (less than one  
 1125  $\mu\text{m}$ ) 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  $\mu\text{m}$  length). 9b: detail of the crown of eroded granules. 10a (P49/3): conical  
 1131 vesicle (161  $\mu\text{m}$  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: Ancyrochitinae 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  $\mu\text{m}$ , except for 4, 7, 8 (10  $\mu\text{m}$ ) and 3, 5 and 10 (1  $\mu\text{m}$ ).  
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  $\text{HNO}_3$ . 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  $\mu\text{m}$  thick. 5: Casts of framboids of pyrite  
1150 after dissolution with  $\text{HNO}_3$ .  
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  $\text{HNO}_3$ .  
1155  
1156 **Plate X.** Scale bar = 100  $\mu\text{m}$ , except for 13 and 21b (50  $\mu\text{m}$ ).  
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 Hérissé 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 Hérissé 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 Hérissé 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 Hérissé 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 Hérissé 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 Hérissé 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 Hérissé et al., 2013. Core sample at  
 1221 67.97 m depth; IGR 72988 (O44/3).  
 1222 18–20: *Euconochitina moussegoudaensis* Paris, in Le Hérissé 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 Hérissé, in Le  
 1235 Hérissé et al., 2013. Core sample at 50.73 m depth; IGR 72958 (S34).  
 1236 8, 11–13: *Tasmanites tzadiensis* Le Hérissé, in Le Hérissé 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 HNO<sub>3</sub>. IGR 72973 (N39/2). 16: biofilm without oxidation by HNO<sub>3</sub> 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

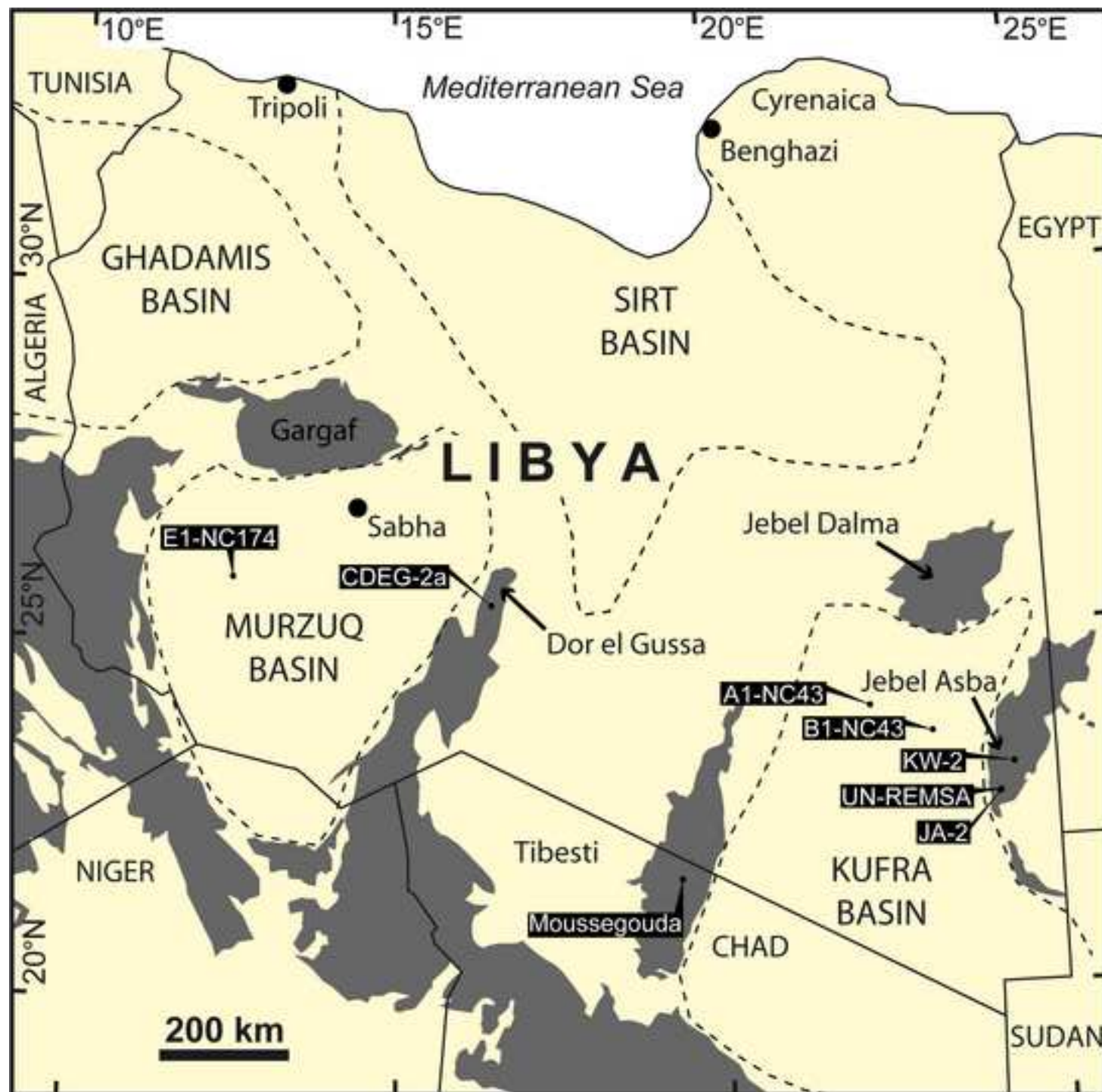


Figure 2

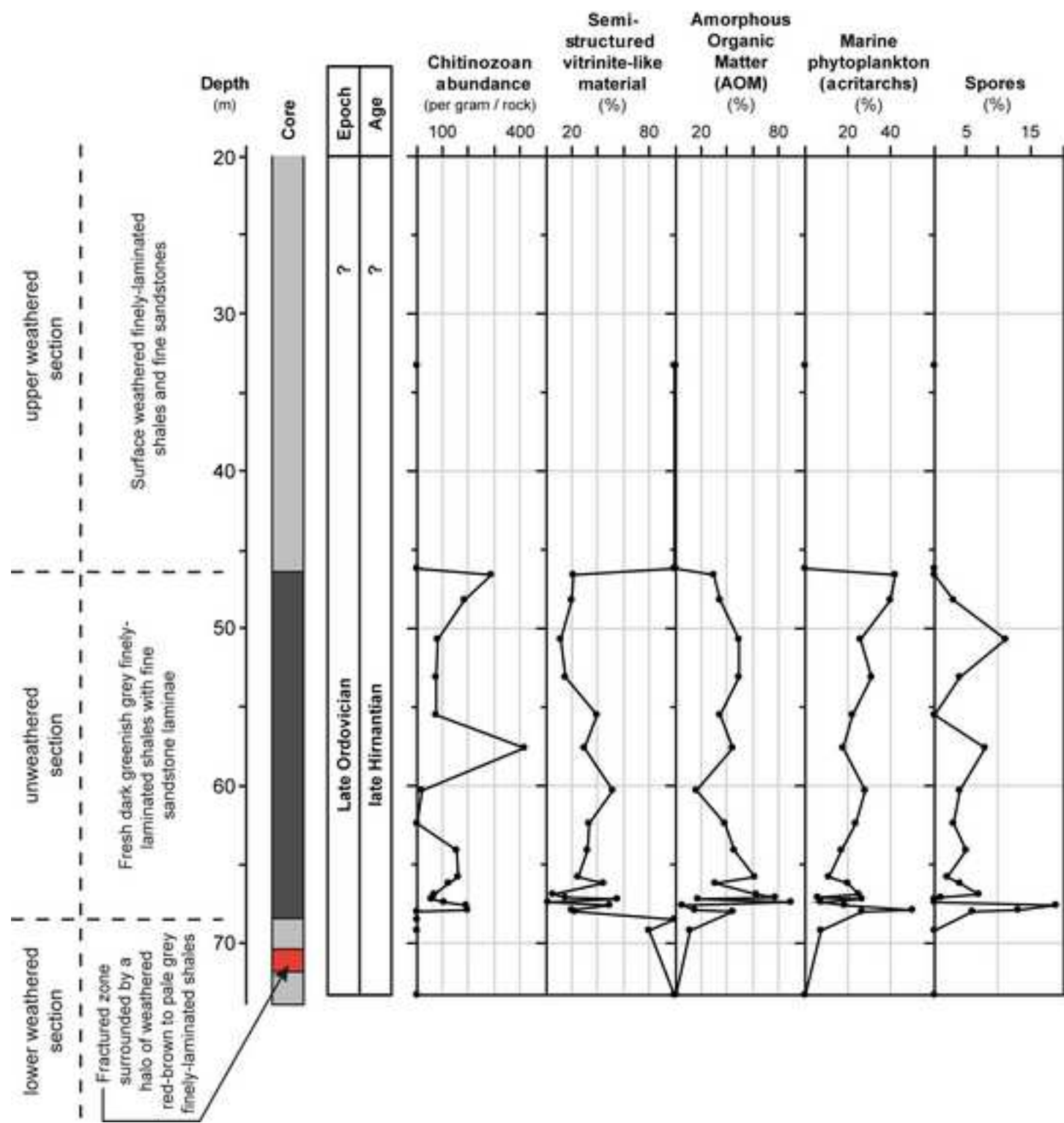


Figure 3

Ordovician		AGE	SELECTED SPECIES
Caradocian	Ashgillian	Silurian	
		Llandoveryian	1. <i>Eupolkoifusa striatifera</i>
			2. <i>Veryhachium trispinosum</i>
			3. <i>Dixallophasis 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>Buedingiisphaeridium</i> sp.
			12. <i>Tetrahedraletes medienensis</i>
			13. <i>Ambitisporites dilutus</i>
			14. <i>Archaeozonotrites 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
			LIBYA
			MURZUQ
		1, 2, 3, 6, 7, 11, 12, 17	Paris et al. (2012)
			GHADAMIS
		1, 2, 3, 7, 9, 12, 14, 17	Beqip (1974) and unpublished data
		1, 2, 3, 6, 11, 12, 13, 17	Molyneux and Paris (1985); Hill and Molyneux (1988)
		Zone LL1-LL2	
			ALGERIA
		1, 2, 3, 7	Jardiné et al. (1974)
		Zone G1-G2	
			MOROCCO
			No previous record from Silurian
			SAUDI ARABIA
		1, 3, 5, 8, 9, 10, 11	Le Hérisse et al. (1995)
		Zone 2-3	
		9, 13, 14, 17	Keegan et al. (1990)
		Zone JS-3	
			JORDAN
			USA
		4, 12, 13, 15, 16	PENNSYLVANIA
			Johnson (1985)

### Figure 4

[illegible]

[illegible]

Table 1

Table 1.

Sample depth (m)	Available sample (g)	Processed sample (g)	SEM observation	Chitinozoan abundance per gram / rock	Sorted %	Biofilm	Scolecodonts	Eurypterids	<i>Tasmanites</i>	Lithology	Traces of weathering
<b>JA-2</b>											
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	
<b>UN-REMSA</b>											
SJS0001		4.0	YES	125	10	X	X			dark silty shale	

Explanation: X (present), XX (abundant)



Table 2

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>Buedingiisphaeridium</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

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>Tetrahedraletes medinensis</i>	<i>Archaeozonotriletes chulus</i> var. <i>chulus</i>	<i>Lophozonotriletes</i> spp.	<i>Tetrahedraletes medinensis</i>	Reticulate spores	<i>Rugosphaera tuscarorensis</i>	<i>Tortotubus protuberans</i>
<b>JA-2</b>															
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															
<b>UN-REMSA</b>															
SJS0001	R				A										R

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



Table 4.

Sample depth (m)	Vitrinite –like, semistructured	Amorphous organic matter	Cutinite	Acritarchs	Inertinite	Vitrinite-like, degraded	Exinite spores	Exinite resinite	Exinite <i>Tasmanites</i>	Intertinite semifusinite
<b>JA-2</b>										
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									
<b>UN-REMSA</b>										
SJS0001	5	89		2		2	2			

Table 5.

Sample depth (m)	R <sub>ch</sub> average	Corrected average	Count	Standard deviation	Minimum	Maximum	R <sub>v</sub> 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

