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Palynology of the Middle Ordovician Hawaz Formation in the Murzuq Basin, southwest Libya

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Twenty nine core and seven cuttings samples were collected from two boreholes penetrating the Middle Ordovician Hawaz Formation in the Murzuq Basin, southwest Libya. The samples were palynologically analysed in order to determine age and depositional environment. The palynological assemblages contain abundant sphaeromorphs, rare but diverse acritarchs, rare chitinozoans, and relatively abundant cryptospores. A total of 26 acritarch species, five chitinozoan species and 17 cryptospore species have been identified. The acritarch and chitinozoan assemblages provide biostratigraphical age dating and indicate that the Hawaz Formation is Mid Ordovician and most likely mid Darriwilian (Llanvirn) in age. The cryptospore assemblage is typical of those from the Mid Ordovician-earliest Silurian and does not permit further age refinement. Based on palynofacies analysis the depositional environment of the Hawaz Formation is interpreted as shallowing upward from nearshore marine inner shelf to marginal marine. The cryptospores provide rare evidence for Middle Ordovician terrestrial vegetation at this very early stage in its development.

Keywords: acritarchs; chitinozoans; cryptospores; palynofacies; Middle Ordovician

1. Introduction

Palynological studies from the Murzuq Basin in southwest Libya are few in comparison to other Palaeozoic basins in Libya (e.g. Ghadamis, Al Kufra, northeast Libya). This study presents the first comprehensive palynological analysis of the Middle Ordovician Hawaz Formation in the Murzuq Basin. Prior to this study, the only available palynological age dating was provided by Aziz (2000) from an unpublished report (COREX 1998). This was based on acritarchs and assigned the Hawaz Formation to the Early to Mid Ordovician. Other previous biostratigraphical work, based on invertebrate macrofossils (graptolites, brachiopods, trilobites), suggested that the formation was Llanvirn in age (Mamgain 1980). Furthermore, trace fossils have been used to tentatively date these and related deposits. On the basis of arthrophycid worm burrows a Mid Ordovician age was suggested (Gundobin 1985; Seilacher 2000) and based on the occurrence of certain ichnospecies of the trace fossil Cruziana an Arenig age was suggested (Seilacher et al. 2002). The aim of this study is to provide a detailed palynological analysis of the Hawaz Formation in the Murzuq Basin in order to determine its age and depositional environments.

2. Geological setting

2.1 Geographical location

The Murzuq Basin of southwest Libya is one of the largest Palaeozoic intracratonic sag basins on the North African Sahara Platform. It is triangular in shape, with an apex oriented to the south towards Chad, and covers an area of over 350,000 km^2 (Bellini & Massa 1980). It is bounded to the north by the Gargaf uplift, to the east by the Tibesti Uplift, and to the west by the Tihemboka Arch. Further south it extends into Niger and is there known as the Jadu Basin (Figure 1).

2.2 Structural framework

The Murzuq Basin has been affected by several compressional and extensional tectonic events. This tectonic activity commenced during the Precambrian creating vertical north-south trending basement faults counterbalanced by conjugated northeast-southwest trending faults (Bellini & Massa 1980; Goudarzi 1980; Al Fasatwi et al. 2000; Echikh & Sola 2000). These Pan-African events were followed by several other tectonic episodes including the Caledonian Orogeny (early-late Silurian) and Hercynian orogeny (Late Carboniferous). These caused folding, faulting and considerable subsidence (Bellini & Massa 1980). A third major tectonic phase was the Tertiary Alpine orogeny. Echikh & Sola (2000) identify seven principle tectonic elements within the Murzuq Basin. From west to east these are: the Tihemokah Arch, Al-Awaynat Trough, Tirinine High, Awbari Trough, Idhain Depression, Brak Bin Ghanimah Uplift and Dur Al Qussah Trough (Figure1). Al Fasatwi et al. (2000) explained that the Murzuq Basin was shaped by two main fault systems. The first system located in the east of the basin is the northeast-southwest trending Dor El Qusseh fault system that forms the boundary with the Dor El Qusseh subbasin. The Brak-Ben Ghenemah Arch, trending northwest-southeast, separates the Dor El Qusseh subbasin from the main Murzuq Basin in the west. These fault zones were still tectonically active from Cambrian to Early Devonian times. During the Jurassic the eastern flank of the basin was uplifted and since then Dor El Qusseh has been a mountain chain. The north-south Tihembokah Arch separates the Murzuq Basin and the Ghadamis Basin in Libya from the Illize Basin in Algeria.

2.3 Stratigraphical framework

The sedimentary succession in the Murzuq Basin unconformably overlies Precambrian rocks and ranges from Cambrian to Cretaceous in age. These sediments are composed mainly of marine siltstone and sandstone and continental sandstone. Many researchers have discussed the stratigraphy of the Murzuq Basin (Mamgain 1980; Bellini & Massa 1980; Castro et al. 1985; Pierobon 1991; Echikh & Sola 2000; Davidson et al. 2000; Sutcliffe et al. 2000; Hallet 2002; McDougall & Gruenwald 2011). These workers divided the sequences into four major sedimentary units: (1) Cambrian–Ordovician; (2) Silurian; (3) Devonian-Carboniferous; (4) Mesozoic. The basement is composed of Precambrian high-grade metamorphic rocks, associated with plutonic rocks, as well as low-grade metamorphic to unmetamorphosed rocks (Mourizidie Formation). These Precambrian rocks are incised by Lower Palaeozoic erosion (Pan-African unconformity) and overlain by a Cambrian–Ordovician clastic sequence called the Gargaf Group (Burollet 1969). The Gargaf Group comprises five formations, in ascending order: Hasawnah, Ash Shabiyat, Hawaz, Melaz Shuqran and Mamuniyat (Figure 2). All boundaries between formations are unconformable, except for the contact between the Ash Shabiyat and Hawaz formations. The Ash Shabiyat and Hawaz formations consist mostly of quartzarenites; the Hasawnah and Mamuniyat formations consist of conglomeratic to microconglomeratic quartzarenites; and the Melaz Shuqran Formation is predominantly a mudstone The Ordovician succession is truncated by the Taconic unconformity and is transgressively overlain by the Silurian Tanezzuft Formation.

2.4 Details of the Hawaz Formation

The Hawaz Formation was first introduced by Massa & Collomb (1960) and named after Jabal Hawaz on the Gargaf Arch. It typically consists of cross-bedded, fine- to medium-grained, quartizitic sandstone with subordinate siltstone and shale containing abundant ichnofossils of the animal burrow Tigillites. The lithology of the lower part of this formation is finer-grained than that of the uppermost As Shabiyat Formation. Vos (1981) suggested that the formation was deposited in a fan delta complex, which prograded across the Gargaf area. Ramos et al. (2006) and De Gibert et al. (2011) suggested that the whole Hawaz Formation was deposited in a shallow marine environment. In the northwestern part of the Murzuq Basin the Hawaz Formation is overlain by shale of the Ordovician Melaz Shuqran Formation.

3. Material and methods

Palynological analysis was carried out on 29 core and 7 cutting samples collected from two boreholes (A28i-NC186 and H2-NC186). Palynomorphs were extracted from shale and siltstone samples using standard palynological techniques: HCl and HF acid maceration followed by heavy mineral separation using zinc bromide. Organic residue was sieved using a 10 µm nylon mesh. Samples were not oxidized. The palynological preparations were studied using light and scanning electron microscopy. All materials are curated in the collections of the Centre for Palynology of the University of Sheffield.

The samples yielded small to moderate amounts of organic matter containing poor to moderately well preserved palynomorphs of low thermal maturity. The assemblages are dominated by sphaeromorphs, but also contain rare but diverse acritarchs, rare chitinozoans, and relatively abundant cryptospores. Systematic description of the palynomorphs is not provided in detail because low numbers of palynomorphs (other than sphaeromorphs) were recovered and no new forms were identified.

4. Systematic palaeontology

4.1 Prasinophycean phycomata

Division CHLOROPHYTA Pascher 1914
Class PRASINOPHYCEAE Christensen 1962

Genus Cymatiosphaera O Wetzel 1933 ex. Deflandre 1954

Type species: Cymatiosphaera radiata O Wetzel 1933

Cymatiosphaera sp. A
Plate 1, figures 5, 6

Description: Vesicle originally spherical to sub-spherical; wall thin, psilate. Surface of vesicle divided into 7-10 polygonal fields delineated by relatively thick membraneous muri 3 to 4 µm in height. No excystment structure observed.

Dimensions: Vesicle diameter 35(40)45 µm (4 specimens measured).

Remarks and comparision: This species is similar in morphology to C. blaisdonica Dorning 1981 but differs in having higher membraneous muri.

Cymatiosphaera sp. B
Plate 1, figure 7

Description: Vesicle originally spherical to sub-spherical; wall thin, psilate. Surface of vesicle divided into 12-16 polygonal fields delineated by thin membraneous muri 3 to 4µm in height. No excystment structure observed.

Dimensions: Vesicle diameter 30(35)40 µm (5 specimens measured).

Remarks and comparision: This species differs from Cymatiosphaera sp. A by having more polygonal fields and thin membraneous muri.

Genus Dictyotidium Eisenack 1955a emend. Staplin 1961

Type species: Dictyotidium dictyotidium (Eisenack) Eisenack 1955a.

Dictyotidium sp. A
Plate 1, figure 8

Description: Spherical to sub-spherical vesicle, smooth, thick walled. The vesicle surface is divided into numerous, fairly uniform polygonal fields. The wall marked by a thickening at the triple junction of the polygonal fields. Excystment structure is unclear.

Dimensions: Vesicle diameter 45(47)50 µm, Wall thickness 1.5(2)2.5 µm (4 specimens measured).

Remarks and comparision: This species differs from D. dictyotum (Eisenack) Eisenack 1955a in having thickenings at the junctions of the polygonal fields.

Genus Leiosphaeridia (Eisenack) Downie & Sarjeant 1963 emend. Turner 1984

Type species: Leiosphaeridia baltica Eisenack 1958.

Leiosphaeridia spp**.**
Plate 2, figure 7

Dimensions: Vesicle diameter 10(40)70 µm (15 specimens measured).

Remarks and comparison: Leiosphaeridia species recorded here are of a wide size range with continuously intermediate sizes and wall thicknesses. It appears there is no reliable way of identifying species.

Genus Pterospermella Eisenack 1972a

Type species**:** Pterospermella aureolata (Cookson & Eisenack) Eisenack 1972a

Pterospermella colbathii Vavrdová 1990b
Plate 3, figure 1-2

1990b Pterospermella colbathii - Vavrdová, p. 240-241; pl. 2, figs. 3, 4, 7, 8.
1999 Pterospermella colbathii - Vecoli, p. 27; pl. 12, fig. 9.

Dimensions: Vesicle diameter 17(24)32 µm, flange width 15(17)20 µm (4 specimens measured).

Remarks and comparisons: The specimens recorded in the current study conform to the original description by Vavrdová (1990b).

Previous stratigraphic record: Arenig of Bohemia (Prague Basin) (Vavrdová 1990b); Darriwillian (Llanvirn) of northern Gondwana (Vecoli & Le Hérissé 2004).

Pterospermella? sp. A
Plate 3, figure 3

Description: Vesicle spherical to sub-spherical, with thick wall, and equatorial flange, about 20% of vesicle diameter. The wall of both vesicle and flange is ?psilate. No excysement structure observed.

Dimensions: Vesicle diameter 45(48)50 µm, flange width 8(10)12 µm (8 specimens measured).

Remarks and comparisons: This species is distinguished from other Pterospermella species in having a thick, non-translucent vesicle wall and a relatively thick, translucent flange.

4.2 Acritarchs

Group ACRITARCHA Evitt 1963
Genus Ampullula Righi 1991 emend. Brocke 1997 emend. Yan & Li 2010

Type species: Ampullula suetica Righi 1991.

Ampullula suetica Righi 1991
Plate 1, figures 1-2

Dimensions: Vesicle diameter 70(77)85 µm, Process length 8(10)12 µm (3 specimens measured).

Remarks and comparison: A. erchunensis Brocke 1997 differs from this species in having numerous processes and a prominent tubular neck.

Previous stratigraphic record: Darriwillian (Llanvirn) of northern Gondwana (Vecoli & Le Hérissé 2004), but in Perigondwana the first appearance of this species is in the Floian (Yan & Li 2010).

Genus Baltisphaeridium Eisenack 1958 ex. Eisenack 1959 emend. Eiserhardt 1989

Type species: Baltisphaeridium longispinosum (Eisenack) Eisenack 1959.

Baltisphaeridium cf. klabavense (Vavrdová) Kjellström 1971
Plate 1, figures 3-4

Dimensions: Vesicle diameter 39(47)55 µm, Process length 18(24)30 µm (4 specimens measured).

Remarks and comparison: B. Klabavense differ from the specimens recorded here, in having more clearly ornamentation of small grana or verrucate elements on the vesicle surface and process wall.

Genus Comasphaeridium Staplin, Jansonius & Pocock 1965 emend. Sargeant and Stancliffe 1994

Type species: Comasphaeridium cometes (Valensi) Sargeant and Stancliffe 1994

Comasphaeridium cf. solare Cramer & Diez 1977
Plate 3, figure 5

Dimensions: Vesicle diameter 15(17)18 µm, Process length 6(7)8 µm (3 specimens measured).

Remarks and comparison: This species is similar in morphology to C. solare Cramer & Diez 1977 from the late Arenig of Morocco but it is smaller in overall size. C. erizum Cramer et al. 1976 differs in that it has process bases that are relatively wider and rapidly taper to form fine needle-like tips.

Genus Elektoriskos Loeblich 1970

Type species: Elektoriskos aurora Loeblich 1970.

Elektoriskos sp. A
Plate 1, figure 9

Description: Spherical to sub-spherical, thin, single walled vesicle bearing, thin, solid, and homomorphic processes more than 40 in number. The processes communicate freely with the vesicle cavity and taper gently to acuminate tips. The wall surface of the vesicle and process is psilate. No excystment structure observed.

Dimensions: Vesicle diameter 16(19)22 µm, Process length 6(7)8 µm (2 specimens measured).

Remarks and comparison: This species differs from Elektoriskos sp. Loeblich 1970 from the mid Silurian in its smaller size and in having long processes.

Genus Frankea Burmann 1970 emend. Servais 1993

Type species Frankea hamata Burmann 1970.

Frankea breviuscula Burmann 1970
Plate 1, figure 10

Dimensions: Vesicle diameter 24(26)28 μm, Process length 10(11)12 μm (2 specimens measured).

Remarks and comparison: These specimens are attributed to Frankea breviuscula based on their triangular vesicle shape, process length and their characteristic palmate termination into three acuminate pinnae.

Previous stratigraphic record: Caradoc of UK (Turner 1982); late Arenig of UK (Turner & Wadge 1979; Rushton & Molyneux 1989); Llanvirn of Germany (Burmann 1970), Czech Republic (Vavrdová 1979), England (Millward & Molyneux 1992) and Belgium (Vanguestaine & Wauthoz 2011); Darriwilian-Sandbian of northern Gondwana (Vecoli & Le Hérissé 2004).

Frankea hamata (Martin) Colbath 1986
Plate 2, figure 3

Dimensions: Vesicle diameter 22(24)26 μm, Process length 5(6)7 μm (2 specimens measured).

Remarks and comparison: This species differs from F. sartbernardense (Martin) Colbath 1986 in having two pinnae at the distal terminations of the processes.

Previous stratigraphic record: Llanvirn of Germany (Burmann 1970); Arenig of England (Turner & Wadge 1979; Rushton & Molyneux 1988; Molyneux 1979; Millward & Molyneux 1992), Belgium (Vanguestaine & Wauthoz 2011); Arenig-Llanvirn of Ireland (Brück & Vanguestaine 2004); Darriwilian-Sandbian of northern Gondwana (Vecoli & Le Hérissé 2004).

Frankea longiuscula? Burmann 1970
Plate 2, figures 1-2

Dimensions: Vesicle diameter 40(44)48 μm, Process length 70(73)76 μm (2 specimens measured).

Remarks and comparison: These specimens are attributed to F. longiuscula? based on their triangular vesicle, process length and the characteristic branched termination of processes into four homomorphic acuminate pinnae.

Previous stratigraphic record: Llanvirn of Germany (Burmann 1970); late Arenig of Jordan (Keegan et al. 1990); Llanvirn of Belgium, Bohemia and Germany (Servais 1993); Llanvirn-Caradoc of northern Gondwana (Vecoli & Le Hérissé 2004); late Arenig-Llanvirn of Saudi Arabia (Le Hérissé et al. 2007); Hirnantian of Turkey (Paris et al. 2007); Mid Ordovician of Belgium (Vanguestaine 2008).

Frankea sp. A
Plate 2, figure 4

Description: Vesicle equilateral to sub-triangular, smooth, thin walled with straight to slightly convex sides. Processes arise from each corner of the vesicle. They are hollow, homomorphic and usually communicate freely with the vesicle cavity although they may be pluged at their bases; their length is approximately equal to the vesicle diameter. They are branched distally into three homomorphic, acuminate pinnae, that are not palmate. No excystment structure observed.

Dimensions: Vesicle diameter 24(26)28 µm, Process length 24(26)28 µm (3 specimens measured).

Remarks and comparison: This species differs from F. sartbernardense (Martin) Colbath 1986 and F. longiuscula Burmann 1970 in the ratio of process length to vesicle diameter.

Genus Helosphaeridium Lister 1970

Type species: Helosphaeridium calvispinulosum Lister 1970

Helosphaeridium? sp. A
Plate 2, figure 5

Description: Vesicle more or less ovoid, moderately thin, single wall. Processes are numerous, small, homomorphic, closey spaced, solid, distal termination seems to be flat or have circular expansions. Excystment formed by equatorial split.

Dimensions: Vesicle diameter 30(35)44 µm, Process length 0.6(1)1.4 µm (4 specimens measured).

Remarks and Comparison: The few specimens recorded are questionably attributed to Helosphaeridium based on the process shape and excystment structure.

Genus Leiofusa Eisenack 1938 emend. Combaz et al. 1967

Type species: Leiofusa fusiformis (Eisenack) Eisenack 1938.

Leiofusa cf. fusiformis Eisenack 1934 ex Eisenack 1938
Plate 2, figure 6

Dimension: Vesicle length 85(92)100 µm, Vesicle widith 20(22)25 µm (5 specimens measured).

Remarks and compression: This species is similar to L. fusiformis Eisenack 1938 but differs in having longer processes and a shorter vesicle length. It differs from L. litotes Loeblich & Tappan 1976, which lacks distinct processes, and L. tumida Downie 1959, that has a more inflated and oval vesicle. L. crassiuscula Burmann

1968 and L. sp. A Vecoli 1999 differ from this species in having longer processes but the vesicle is similar.

Genus Liliosphaeridium utela & Tynni, 1991 emend. Vecoli et al 1995

Type species: Liliosphaeridium kaljoi Uutela & Tynni, 1991

Liliosphaeridium? sp. A
Plate 3, figure 4

Description: Vesicle originally spherical to subspherical with a relatively thin, psilate wall. Processes are 6-8 in number and flair distally. They do not communicate with the vesicle cavity. Excystment structures not clearly observed.

Dimensions: Vesicle diameter 40(45)50 μm, Process length 13(14)25 μm (2 specimens measured).

Remarks and comparison: These extremely rare specimens, with 6-8 processes that appear to flair distally and do not communicate with the vesicle cavity, potentially can be accommodated by the genus Liliosphaeridium.

Genus Lophosphaeridium Timofeev 1959 ex Downie 1963 emend. Lister 1970

Type species: Lophosphaeridium rarum Timofeev 1959 ex Downie 1963.

Lophosphaeridium cf. fuscipetiolatum (Cramer & Díez) Vecoli 1999
Plate 2, figure 8

Dimensions: Vesicle diameter 60(65)70 μm (3 specimens measured).

Remarks and comparison: The specimens recorded in the current study are very similar in morphology and size to the specimens illustrated by Cramer & Diez (1977) from the Arenig of Morocco and by Vecoli (1999) from the Llanvirn of Algeria, but these have more 'granules' which consist of low conate and flat verrucate elements.

Genus Micrhystridium Deflandre 1937 emend. Staplin 1961 emend. Lister 1970

Type species: Micrhystridium inconspicuum (Deflandre) Deflandre 1937 emend Deflandre & Sargeant 1970

Micrhyhistridium cf. equispinosum Downie 1982
Plate 2, figure 9

Dimensions: Vesicle diameter 14(16)18 μm, Process length 8(9)10 μm (3 specimens measured).

Remarks and comparison: This species differs from M. stellatum Deflandre 1945 in the shape and great number of its process. It is very similar to M. equispinosum Turner 1984 in the vesicle and processes morphology but it differs in having shorter processes. M. filiferum Rasul 1979 has slightly longer processes.

Genus Pirea Vavrdová 1972

Type species: Pirea dubia Vavrdová, 1972

Pirea? sp.A
Plate 2, figure 10

Description: Unilayered, thin, smooth pear- to bottle-shaped vesicle with a long, conical, hollow apical process tapering gradually from the vesicle and closed distally with presence dark in colour at the extreme distal termination of apical pole. The process appears to have a plug at the base (but it is not clear). No excystment structure observed.

Dimensions: Vesicle diameter 55(60)65 μm, Process length 30(33)35 μm (5 specimens measured).

Remarks and comparison: This species conforms to the genus Pirea in general morphology. However, it is characterized, and possibly distinguished from that genus, by a number of features. It has a long, conical, hollow apical process that tapers gradually from the vesicle. This apical process is closed distally (as indicated by the dark colouration at the extreme distal termination of apical pole) and appears to have a plug at its base.

Genus Poikilofusa Staplin, Jansonius & Pocock 1965

Type species: Poikilofusa spinata Staplin, Jansonius & Pocock 1965

Poikilofusa cf. ciliaris Vecoli 1999
Plate 2, figure 11

Dimensions: Vesicle length 95(100)105 μm, Vesicle width 15(20)25 μm (5 specimens measured).

Remarks and comparison: P. Ciliaris differ from the specimens recorded here in having less distinct processes and a vesicle that clearly is ornamented with numerous spines that are ± regularly-spaced and arranged in longitudinal raws. P. spinata Staplin et al. 1965, has longer apical processes and different sculpturing (i.e. longer, irregularly-spaced, conically-based spines).

Genus Stellechinatum Turner, 1984

Type species: Stellechinatum celestum (Martin, 1969) Turner, 1984.

Stellechinatum spp.
Plate 4, figure 3, 4

Description: Smooth, hollow, single-layered, polygonal vesicle bears wide based processes 7-10 in number. The processes are hollow and homomorphic and taper gradually to acuminate tips and communicating freely with the vesicle. The surface of vesicle presents a finer granulation, wheares the processes have a fine to well developed thin spine. No excystment structure observed.

Dimensions: Vesicle diameter 22(39)55 µm, Process length 5(13)20 µm (4 specimens measured).

Remarks and Comparison: Stellechinatum celestum (Martin) Turner 1984 differs from the specimens recorded here in having processes that are ornamented with slender, short spines.

Genus Stelliferidium Deunff et al.1974

Type Species: Stelliferidium striatulum (Vavrdová) Deunff et al. 1974

Stelliferidium philippotii Henry 1966 emend. Deunff et al. 1974
Plate 3, figure 6

Dimensions: Vesicle diameter 38(42)49 µm, Process length 3(4)5 µm (5 specimens measured).

Remarks and comparison: The Hawaz specimens are similar to those illustrated by Vecoli (1999) from the Llanvirn of Tunisia. It differs from S. velatum Vecoli 1996 in having more numerous and smaller processes and an appreciably larger vesicle. S. striatulum (Vavrdová) Deunff et al. 1974 has fewer and longer processes.

Previous stratigraphic record: Darriwilian (Llanvirn) of northern Gondwana (Vecoli & Le Hérissé 2004).

Stelliferidium striatulum (Vavrdová) Deunff et al.1974
Plate 3, figure 7

Dimensions: Vesicle diameter 38(42)42 µm, Process length 7(9)10 µm (3 specimens measured).

Remarks and comparison: It is difficult to distinguish this species from S. stelligerum Górka 1967 but as stated by Albani (1989) S. striatulum has more robust and fewer processes.

Previous stratigraphic record: Arenig of Belgium (Martin & Rickards 1979) and Argentina (Achab et al. 2006); Tremadocian of Belgium (Martin 1969); Llanvirn of Jordan (Keegan et al. 1990) and Oman (Molyneux et al. 2006); Late Cambrian-early Arenig of British Isles (Downie 1984); Llandeilo of South Wales (Turner 1985); early to middle Arenig of southeast Ireland (Maziane-Serraj et al. 2000); Arenig-early Caradoc, northern Gondwana (Vecoli & Le Hérissé 2004); late Arenig-late Llanvirn of Saudi Arabia (Le Hérissé et al. 2007). Vecoli (1999) commented that this species attained its acme in the early-mid Llanvirn and does not occur in either pre-Arenig or post-Llandeilo sediments and all occurrences recorded beyond this range are misidentified or reworked; Lower-Mid Ordovician of China (Yan et al. 2013).

Stelliferidium stelligerum (Górka) emend. Deunff et al.1974

Plate 3, figures 8

Dimensions: Vesicle diameter 35(40)45 µm, Process length 4(7)10 µm (3 specimens measured).

Remarks and comparison: As discussed by Albani (1989) S. stelligerum Górka 1967 is distinguished from S. striatulum in having a smaller excystment structure and more processes.

Previous stratigraphic record: Early Tremadocian of Iran (Ghavidel-syooki 2006); Caradoc of England (Turner 1982; reworked specimens); Arenig of Iran (Ghavidel-syooki 2001); Floian-Darriwilian of Argentina (Aráoz 2009); early Arenig of Russia (Raevskaya et al. 2004); Tremadocian-Darriwilian of northern Gondwana (Vecoli & Le Hérissé 2004).

Stelliferidium cf. simplex (Deunff) Deunff et al.1974
Plate 4, figures 1-2

Dimensions: Vesicle diameter 34(34)45 µm, Process length 6(8)9 µm (2 specimens measured).

Remarks and comparison: The specimens included here have short processes with acuminate or capitate distal terminations. They are very similar in morphology to Stelliferidium sp. recorded by Ribecai & Tongiorgi (1995) from the Arenig of Sweden.

Previous stratigraphic record: Early to middle Arenig of southeast Ireland (Maziane-Serraj et al. 2000); Tremadocian-Arenig of Iran (Ghavidel-syooki 2001); Tremadocian of Oman (Molyneux et al. 2006) and northern Gondwana (Vecoli & Le Hérissé 2004).

Genus Uncinisphaera Wicander 1974

Type Species: Unicinisphaera lappa Wicander 1974

Uncinisphaera fusticula Vecoli 1999
Plate 4, figures 5-6

Dimensions: Vesicle diameter 40(43)45 µm, Process length 10(13)15 µm (3 specimens measured).

Remarks and comparison: The specimens recorded in this study are similar to those described by Vecoli (1999).

Previous stratigraphic record: Mid Arenig-early Caradoc of northern Gondwana (Vecoli & Le Hérissé 2004); Early-Mid Ordovician of Saudi Arabia (Le Hérissé et al. 2007).

Genus Veryhachium Deunff 1954 ex Downie 1959 emend. Turner 1984

Type species: Veryhachium trisulcum Deunff 1951 ex Deunff 1959

Veryhachium cf. lairdii Deflandre 1947 ex Loeblich 1970
Plate 4, figure 7

Dimensions: Vesicle diameter 20(23)26 µm, Process length 5(8)10 µm (3 specimens measured).

Remarks and comparison: The specimens recorded in this study are distinguished from V. lairdii Deflandre 1947 ex Loeblich 1970 and V. oklahomense Loeblich 1970 by the ratio of process length to vesicle diameter. In addition the processes are narrow proximally and acuminate distally. They are very similar to V. aff. lairdii from the Upper Ordovician of northeast Libya described by Molyneux (1988) but it differs in having shorter processes. This taxon could simply be considered as belonging to the Veryhachium lairdii group sensu Servais et al. (2007).

Veryhachium trispinosum (Eisenack) Stockmans & Willière 1963
Plate 5, figure 1

Dimensions: Vesicle diameter 24(36)48 µm, Process length 13(26)40 µm (5 specimens measured).

Remarks and comparison: This species is abundant in the studied samples and shows a variation in process length relative to vesicle diameter. This species differs from V. downiei Stockman & Williere 1963 in being larger in size and from V. irroratum Loeblich & Tappan 1969 and Villosacapsula setosapellicula (Loeblich) Loeblich & Tappan 1976 in having a smooth vesicle wall rather than grana or microspinae. This taxon could simply be considered as belonging to the Veryhachium trispinosum group sensu Servais et al. (2007).

Previous stratigraphic record: This species has a world-wide distribution and ranges from the Ordovician through Permian.

4.2 Chitinozoans

The taxonomic and morphological terminology proposed by Paris et al. (1999) is adopted here. The measurements used are: L = total length; Lp = chamber length; Dp= chamber diameter; Dc= oral tube diameter. All measurements were made by means of both light and scanning electron microscopy.

Order PROSOMATIFERA Eisenack 1972b
Family CONOCHITINIDAE Eisenack 1931 emend. Paris 1981
Subfamily CONOCHITINAE Paris 1981
Genus Conochitina Eisenack 1931 emend. Paris, Grahn, Nestor & Lakova 1999

Type species:Conochitina claviformis Eisenack 1931

Conochitina sp.A
Plate 5, figures 4-5

Description: Conochitina species with elongated sub-cylindrical chamber. The neck is undifferentiated with an absence of shoulders and flexure. The flanks are straight and taper towards the aperture. The base is convex with broadly rounded basal margin and possesses a short copula or mucron at its centre. The vesicle wall covered with dense grana.

Dimensions: L: 426(428)430 µm, Dp: 70(85)100 µm (3 specimens measured).

Remarks and comparison: C. minnesotensis Stauffer 1933 differs from this species in having a smooth vesicle wall

Genus Euconochitina Taugourdeau 1966 emend. Paris et al. 1999

Type species: Euconochitina conulus Eisenack 1955b.

Euconochitina brevis Taugourdeau & de Jekhowsky 1960
Plate 5, figure 6

Dimensions: L: 185(188)190 µm, Dp: 76(79)82 µm, Dc: 52(55)58 µm (3 specimens measured).

Remarks and comparison: This species is distinguished from other Euconochitina species by having a stocky, tapered, sub-cylindrical vesicle with straight flanks. Wang & Chen (1992) discussed the intraspecific variation of E. brevis based on Silurian specimens and found that the shape of this species varies from squat to slender. The stouter specimens have an outline recalling that of species of Eisenackitina Jansonius 1964 restrict. Paris 1981, but differs in the lack of ornamentation.

Previous stratigraphic record: This species has a wide geographic distribution and a very long range, although these have probably been overextended due to dubious identifications. It has been reported from the Ordovician to Early Silurian (Llandovery) of Algeria (Taugourdeau & de Jekhowsky 1960); Middle Ordovician of southwest France (Taugourdeau 1961); Silurian of Spain (Cramer 1967); Arenig of China (Chen & Zhang 2005) and Canada (Achab 1986b); late Floian–Dapingian (Arenig) of China (Chen et al. 2009).

Subfamily EREMOCHITININAE Paris 1981
Genus Siphonochitina Jenkins 1967

Type species: Siphonchitina formosa Jenkins 1967

Siphonochitina formosa Jenkins 1967
Plate 5, figure 7

Dimensions: L: 300(305)310 µm, Dp: 55(58)60 µm, Dc: 40(43)45 µm (4 specimens measured).

Remarks and comparison: The membranous bulb appears to be twisted and broken in all of the specimens reported in this study. Specimens recorded by Jenkins

(1967) have a longer membranous bulb (i.e. unbroken) than those in this study but are otherwise identical.

Previous stratigraphic record: This species has been reported from the mid Darriwilian of Shropshire (Jenkins 1967), France (Paris 1981) and western Libya (Combaz & Poumot 1962). It has also been reported from the mid-late Darriwilian Hanadir Member of the Qasim Formation in Saudi Arabia (e.g. McClure 1988; Al-Hajri 1995; Le Hérissé et al. 2007). The total range of the index species S. formosa is considered to define the mid Darriwilian S. formosa Biozone of northern Gondwana (Paris 1990; Webby et al. 2004).

Subfamily VELATACHITININAE Achab et al. 1993
Genus Velatachitina Poumot 1968

Type species: Velatachitina nebulosa Poumot, 1968.

Velatachitina sp.A
Plate 5, figure 8

Description: Velatachitina species with sub-cylindrical chamber. The neck is undifferentiated. The vesicle is entirely enclosed within a thin, membranous sleeve which usually extends below the base of the chamber. The granules on the vesicle are artefacts caused by impressions of pyrite crystal.

Dimensions: L: 265(268)272 µm, Dp: 90(95)100 µm (2 specimens measured).

Remarks and comparison: The pyrite crystal damage on these specimens (e.g. Plate 5, figure 8) precludes assignment to V. nebulosa Poumot 1968.

Subfamily BELONECHITININAE Paris 1981
Genus Belonechitina Jansonius 1964

Type species: Conochitina micracantha subsp. robusta Eisenack 1959.

Belonechitina micracantha Eisenack 1931
Plate 5, Figure 3

Dimensions: L: 123(231)340 µm, Dp: 61(84)106 µm, Dc: 31(59)88 µm (5 specimens measured).

Remarks and comparison: The spiny ornamentation which characterizes all Belonechitina species was the main character proposed by Eisenack (1931) for B. micracantha. Subsequently, many other species have been excluded from this group (e.g. B. arabiensis, B. pseudoarabiensis and B. postrobusta). However, it is still difficult to separate the numerous poorly-defined forms and they are assigned here to the inclusive taxon B. micracantha. This view was previously adopted by several authors (e.g. Oulebsir & Paris 1995; Samuelsson & Verniers 2000; Bourahrouh et al. 2004; Paris et al., 2007). B. parvispinata Soufiane & Achab 2000 is differentiated from this form by its club-shaped chamber. B. arabiensis Al-Ghammari, Booth &

Paris 2010 and B. ghabaensis Al-Ghammari, Booth & Paris 2010 are generally smaller in overall size with well-differentiated flexure.

Previous stratigraphic record: Ordovician of northeast Libya (Molyneux & Paris 1985); Llanvirn-Caradoc of Canada (Achab & Asselin 1995) and Scandinavia (Grahn & Nõlvak 2007); Arenig-Caradoc of Saudi Arabia (Al-Hajri 1995); Caradoc of USA (Siesser et al. 1998); Darriwilian of Australia (Winchester-Seeto et al. 2000; Quintavalle & Playford 2006), Estonia (Tammekänd et al. 2010) and Turkey (Paris et al. 2007); late Katian-Ashgill of Morocco (Bourahrouh et al. 2004); Darriwilian-Dapingian of Sweden (Vandenbroucke 2004); Ashgill, UK (Van Nieuwenhove et al. 2006); Caradoc-early Ashgill, Belgium (Vanmeirhaeghe 2006) and Morocco (Le Heron et al. 2008); Katian-Hirnantian of northern Iran (Ghavidel-syooki & Vecoli 2008); Caradoc of Belgium (Vanmeirhaeghe 2006), UK (Vandenbroucke et al. 2008); Caradoc-Ashgill of Morocco (Bourahrouh et al. 2004), Hirnantian of the Baltic (Kaljo et al. 2008); Ashgill of UK (Van Nieuwenhove et al. 2006); Darriwilian-Hirnantian of China (Xiaofeng & Xiaohong 2004).

4.3 Cryptospores

Cryptospore genera are arranged alphabetically in groups based on gross morphology: monads, dyads, tetrads, hilate cryptospores. Synonomy lists are only provided for taxa that are not well known.

CRYPTOSPORE MONADS

Genus Sphaerasaccus Steemans et al. 2000

Type species: Sphaerasaccus glabellus Steemans et al.2000

Sphaerasaccus glabellus Steemans et al. 2000
Plate 6, figure 10

1996 Laevigate monads enclosed with a laevigate envelope – Wellman, p. 118; pl. 3, figs. 18-20
2000 Sphaerasaccus glabellus – Steemans et al., p. 102; pl. 4, figs. a-b
2004 Sphaerasaccus glabellus – Rubinstein& Vaccari, p. 1047, text-figure 4c.
2005 Sphaerasaccus glabellus - Rubinstein et al., pl. 1, fig. 13.
2010 Sphaerasaccus glabellus - Rubinstein et al., fig. 2 (e, f).

Dimensions: 25(30)35 µm (5 specimen measured).

Remarks and Comparison: This species comprises a laevigate monad enclosed within a laevigate envelope.

Previous stratigraphic record: Early and Mid Ordovician of Argentina (Rubinstein et al. 2010); Caradoc of southern Britain (Wellman 1996); Hirnantian-Llandovery of Argentina (Rubinstein & Vaccari 2004); Llandovery of Saudi Arabia (Steemans et al. 2000) and Paraguay (Mauller et al. 2004).

Microgranulate monads
Plate 6, figure 16

Description: Monad cryptospore oval to sub-circular in outline. Exospore ornamented with micrograna less than 1.0 µm in length.

Dimensions: 24(26)28 µm (4 specimens measured).

CRYPTOSPORE DYADS

Genus Dyadospora Strother & Traverse 1979 emend. Burgess & Richardson 1991

Type species: Dyadospora murusattenuata Strother & Traverse 1979

Dyadospora murusdensa Strother & Traverse 1979 emend. Burgess & Richardson 1991
Plate 6, figure 2

Dimensions: 24(36)50 µm (10 specimens measured).

Previous stratigraphic record: D. murusdensa is a widely reported taxon with a worldwide distribution from the Mid Ordovician-Early Devonian.

Genus Pseudodyadospora Johnson 1985

Type species: Pseudodyadospora laevigata Johnson 1985

Pseudodyadospora laevigata Johnson 1985
Plate 6, figure 7

Dimensions: 35(40)45 µm (8 specimens measured).

Previous stratigraphic record: P. laevigata is a widely reported taxon with a worldwide distribution from the Mid Ordovician-Early Silurian.

Pseudodyadospora petasus Wellman & Richardson 1993
Plate 6, figure 8

Dimensions: 25(33)45 µm (10 specimens measured).

Remarks: This species is characterized by its thin distal walls that are invaginated.

Previous stratigraphic record: P. petasus is a widely reported taxon with a worldwide distribution from the Late Ordovician-Early Devonian.

Genus A. Steemans et al. 2000

Genus A. Species A Steemans et al. 2000
Plate 6, figure 15

Dimensions: 45(48)50 µm (2 specimens measured).

Remarks and Comparison: This species is similar in morphology to the pseudodyad described by Steemans et al. (2000) from the Llandovery of Saudi Arabia but it larger in size. Pseudodyadospora sp. B Richardson 1988 has the pseudodyad wall ornamented with small grana.

Previous stratigraphic record: Llandovery of Saudi Arabia (Steemans et al. 2000).

CRYPTOSPORE TETRADS
Genus Rimosotetras Burgess, 1991

Type species: Rimosotetras problematica Burgess 1991

Rimosotetras problematica Burgess 1991
Plate 6, figure 9

Dimensions: 32(41)45µm (6 specimen measured).

Remarks and comparison: This species is similar to Tetrahedraletes medinensis Strother & Traverse 1979 emend. Wellman & Richardson 1993 except that the component spores are very loosely attached.

Previous stratigraphic record: R. problematica is a widely reported taxon with a worldwide distribution from the Mid Ordovician-Early Devonian.

Genus Tetrahedraletes Strother & Traverse 1979 emend. Wellman & Richardson 1993

Type species Tetrahedraletes medinensis Strother & Traverse 1979

Tetrahedraletes medinensis Strother & Traverse 1979 emend. Wellman & Richardson 1993.
Plate 6, figure 11

Dimensions: 25(36)45 µm (15 specimens measured).

Previous stratigraphic record: T. medinensis is a widely reported taxon with a worldwide distribution from the Early Ordovician-Early Devonian.

Genus Tetraplanarisporites Wellman et al. 2015

Type species: Tetraplanarisporites laevigatus Wellman et al. 2015

Tetraplanarisporites laevigatus Wellman et al. 2015

Plate 6, figure 14

Dimensions: 31(39)46 µm (8 specimens measured).

Previous stratigraphic record: Late Ordovician-earliest Silurian of Saudi Arabia (Wellman et al. 2015); Ashgill-Hirnantian, Iran (Ghavidel-Syooki, 2016)

Genus Velatiteras Burgess 1991

Type species: Velatiteras laevigata Burgess 1991

Velatiteras laevigata Burgess 1991
Plate 6, figure 13

Dimensions: 35(38)40 µm (4 specimens measured).

Remarks and comparison: The envelope in Velatiteras reticulata Burgess 1991 is ornamented with muri forming a reticulum and the envelope in Velatiteras rugulata Burgess 1991 is ornamented with sinuous to convolute and anastomosing rugulae.

Previous stratigraphic record: V.laevigata is a widely reported taxon with a worldwide distribution from the Mid Ordovician-Early Devonian.

Tetrad sp. A
Plate 6, figure 12

Description: Naked tetrad with an ornament of rugulae.

Dimensions: 25(27)28 µm (2 specimens measured).

Remarks and comparison: This form is very rare but noteworthy in that it is unusual to find naked permanent tetrads that are ornamented in the Ordovician.

HILATE CRYPTOSPORES

Genus Chelinohilates Richardson 1996

Type species: Chelinohilates erraticus Richardson 1996

Chelinohilates maculatus Steemans et al. 2000
Plate 6, figure 1

Dimensions: 42(47)51 µm (8 specimens measured).

Remarks and comparison: The specimens recorded in this study are similar to those described by Steemans et al. (2000) from the Llandovery of Saudi Arabia but are larger in overall size.

Previous stratigraphic record: Silurian of Saudi Arabia (Steemans et al. 2000).

Genus Hispanaediscus Cramer emend. Burgess & Richardson 1991

Type species: Hispanaediscus verrucatus Cramer 1966 emend. Burgess & Richardson 1991

Hispanaediscus? verrucatus Cramer 1966 emend. Burgess & Richardson 1991
Plate 6, figure 3

Dimensions: 20(25)28 µm (4 specimens measured).

Remarks and comparison: The nature of the proximal face is unclear in the specimens. H. rugulatus Cramer 1966 emend. Burgess & Richardson 1995 is similar but has murornate/rugulate proximal walls. H. wenlockensis Cramer 1966 emend. Burgess & Richardson 1991 is larger.

Previous stratigraphic record: Pridoli of Britain (Burgess & Richardson 1991); Silurian of Canada (Beck & Strother 2001) and China (Wang et al. 2005); Lochkovian of Saudi Arabia (Steemans et al. 2007); Pridoli of Brazil (Steemans et al. 2008); Silurian-Devonian of North Africa (Spina & Vecoli 2009).

Hispanaediscus cf. wenlockensis Burgess & Richardson 1991
Plate 6, figure 4

Description: Monad cryptospore with sub-circular or circular amb, crassitude equatorial to sub-equatorial. Proximal hilum laevigate. Distal surface ornamented with densely and closely packed verrucae.

Dimensions: 45(48)50 µm (4 specimen measured).

Remarks and comparison: The specimens recorded here are similar in distal ornamentation to H. wenlockensis Burgess & Richardson 1991 but differ in that the proximal hilum is laevigate and lacks the proximal radial folds or muri. They are very similar to H. cf. wenlockensis recorded by Wellman et al. (2000) from the Ordovician-Silurian of Saudi Arabia but are larger in overall size.

Genus Laevolancis Burgess & Richardson 1991

Type species: Laevolancis (Archaeozonotriletes) divellomedia (Chibrikova) Burgess & Richardson 1991

Laevolancis chibrikovae Steemans et al. 2000
Plate 6, figure 5

Dimensions: 30(32)34 µm (8 specimens measured).

Remarks and comparison: This species is similar to Laevolancis divellomedium, but the border of the hilum is sometimes partially torn, indicating that the hilate cryptospores are physically separated from permanent dyads. Imperfectotriletes vavrdovae (Richardson) Steemans et al. 2000, differs by having an irregular trilete crack.

Previous stratigraphic record: Caradoc of UK (Wellman 1996); Late Ordovician of China (Wang et al. 1997); Llandovery of Saudi Arabia (Steemans et al. 2000; Wellman et al. 2000) and China (Wang & Zhang 2010); Hirnantian-Rhuddanian of Argentina (Rubinstein et al. 2004).

Laevolancis divellomedium Burgess & Richardson 1991
Plate 6, figure 6

Dimensions: 20(30)39µm (8 specimen measured).

Previous stratigraphic record: This widely reported taxon with a worldwide distribution from the Late Ordovician-late Devonian.

4.5 Incertae sedis

Genus Virgatasporites Combaz 1967
Type species: Virgatasporites rudii Combaz 1967

Virgatasporites cf. rudii Combaz 1967
Plate 5, figure 2

Dimensions: 25(33)40µm (3 specimen measured).

Remarks and Comparison: The specimens recorded in this study are very similar to V. rudii recorded by Vecoli (1999) from the Tremadocian of Tunisia, but it differs slightly in the vesicle thickness and in lacking a circular aperture in the central area as seen in the specimens illustrated by Vecoli (1999, pl. 15, fig. 8). V. baccatus Vavrdova 1990a differs from this species, in having thicker, less densely packed, radial muri and has a triangular or slit like aperture in central area

5. Palynostratigraphy

The palynomorph assemblages recorded from all of the samples are essentially similar and belong to the same acritach, chitinozoan and cryptospore assemblage. The acritarch and chitinozoan assemblage enables biostratigraphical age dating and indicates that the Hawaz Formation is Mid Ordovician and most likely mid Darriwilian (Llanvirn) in age. The cryptospore assemblage is of limited biostratigraphical value other than confirming a general Mid to Late Ordovician age. The most relevant summary of biostratigraphically significant Ordovician acritarch ranges was published by Vecoli & Le Hérissé (2004). It provides comprehensive and refined biostratigraphical ranges of acritarchs from the northern Gondwana margin and is used here to age constrain the described acritarch assemblage. In addition, correlation with other zonation schemes previously established in North Africa (Algeria, Tunisia and northwest Libya), Saudi Arabia and Jordan is attempted. The biozonation scheme of chitinozoans in Saudi Arabia by Al-Hajri (1995) and Paris et al. (1995, 2000a) and in northern Gondwana by Paris (1990) and Webby et al. (2004) provide the basis for correlation and age assignment for the chitinozoan

Assemblage Zone. A distribution chart of palynomorphs recovered from the two studied wells is provided in Figures 3-4.

Acritarch Assemblage (Ac-1)

Composition: The acritarch assemblage is defined by the occurrence of Stelliferidium striatulum, S. philippoti, S. stelligerum, Uncinisphaera fusticula, Ampullula suetica, Pterospermella colbathii, Frankea breviuscula, F. Longiuscula?, and F. hamata. Other associated taxa include Leiofusa cf. fusiformis Baltisphaeridium cf. klabavense, Poikilofusa cf. ciliaris, Micrhystridium cf. equispinosum, Dictyotidium sp. A, Elektoriskos sp. A, Helosphaeridium? sp. A, Comasphaeridium cf. solare, Liliosphaeridium sp. A, Stellechinatum spp., Lophosphaeridium cf. fuscipetiolatum, Stelliferidium simplex and Veryhachium cf. lairdii. Long ranging taxa also occur (e.g. V. trispinosum group and Leiosphaeridia spp.).

Occurence: Well H2-NC186 (core, cuttings interval 4608ft.-5200ft.), Well A28i-NC186 (core interval depth 4518ft.-4723ft.)

Age assessment and correlation: This assemblage is assigned to the Mid Ordovician, and most likely to the Mid Darriwilian (Llanvirn) based on the occurrence of biostratigraphically important acritarch taxa such as Pterospermella colbathii, S. philippoti and A. suetica. Vecoli & Le Hérissé (2004) documented the above taxa from the Darriwilian of northern Gondwana, but we should mention here that the FAD of A. suetica is Floian in Perigondwana (Kui et al. 2010). In addition to these taxa, Vecoli & Le Hérissé (2004) documented other acritarchs that span the Darriwilian of northern Gondwana, such as F. hamata, F. breviscula, F. longiscula, S. striatulum and U. fusticula, which are also recorded in the present assemblage. U. fusticula is recorded from the Darriwilian of Saudi Arabia (Molyneux & Al-Hajri 2000; Le Hérissé et al. 2007). In Oman S. striatulum is recorded from the Darriwilian by Droste (1997) and Molyneux et al. (2006). Characteristic species recorded by Keegan et al. (1990) in Zone JO-3 of the Darriwilian (Llanvirn) in Jordan are S. striatulum. The occurrences of A. suetica, S. philippoti and P. cobathii indicate that this assemblage is not older than the Darriwilian (Llanvirn) as these species are unknown from pre-Darriwilian (Llanvirn) strata in northern Gondwana (Vecoli & Le Hérissé 2004). The age assignment is supported also by the absence of typical Late Ordovician (Sandbian, Katian and Hirnantian) species.

Chitinozoan Assemblage (Ch-1)

Composition: The chitinozoan assemblage is characterized by the occurrence of Siphonochitia formosa, and other associated taxa including Velatochitina sp. A and Conochitina sp. A. Long ranging taxa also occur (e.g. Belonechitina micracantha and Euconochitina brevis).

Occurrence: Well H2-NC186 (core, cutting interval 4833ft.-5040ft.), Well A28i-NC186 (core interval depth 4644ft.-4723ft.)

Age assessment and correlation: In general the chitinozoans recovered from the Hawaz Formation are rare and relatively poorly preserved (most of them are fragmented). This assemblage is assigned to the Mid Ordovician, and most likely to the Darriwilian (Llanvirn) based on the occurrence of the biostratigraphically important chitinozoan S. formosa. This species is reported from the mid Darriwilian of western Libya (Combaz & Poumot 1962), Shropshire (Jenkins 1967) and France (Paris 1981), and is described from the mid-late Darriwilian Hanadir Member of the Qasim Formation in Saudi Arabia (McClure 1988; Al-Hajri 1995; Le Hérissé et al. 2007). The total range of the index species S. formosa is considered to define the mid Darriwilian S. formosa Biozone of northern Gondwana (Paris 1990; Webby et al. 2004).

In light of the occurrence of S. formosa, the present assemblage is attributed to the mid Darriwilian. It is noteworthy that in the British Ordovician chronostratigraphy scheme, this assemblage is attributed to the early but not earliest Llanvirn.

Cryptospore Assemblage (Cr-1)

Composition: Cryptospores are reasonably abundant.

Occurrences: Well H2-NC186 (core, cutting interval 4606ft.-5200ft.), Well A28i-NC186 (core interval depth 4518ft.-4723ft.)

Age assessment and correlation: Mid Ordovician-earliest Silurian cryptospore assemblages are similar worldwide and of limited use in biostratigraphical studies. The cryptospore assemblages reported herein is similar to those previously reported from the Mid Ordovician-earliest Silurian of northern Gondwana and at present does not help refine the acritarch-based biostratigraphical age dating.

6. Palaeoenvironmental interpretation based on palynofacies analysis

6.1 Palynofacies methods and classification

The term 'palynofacies' was first introduced by Combaz (1964) based on a palynological study of Lower Palaeozoic deposits from North Africa. Numerous palynofacies classification schemes have been proposed (reviewed in Van Bergen et al. 1990; Tyson 1995; Batten 1996; Traverse 1994, 2007) and their use tends to vary according to the nature and aims of a particular study. In this study the classification schemes of Van Bergen et al. (1990), Tyson (1995) and Batten (1996) are used with some modifications. Palynomorphs/palynodebris are divided into three basic categories: palynomorphs; structured organic matter; structureless organic matter (AOM). Classification of AOM is problematic and several authors have recommended different ways of classifying it (e.g. Combaz 1980; Masran & Pocock 1981; Masran 1984). Batten (1983) preferred to describe its general appearance without formally categorizing it from the point of view of either morphology or biological origin. In this study we divided the AOM into either yellow-brown or dark-brown as these two types form distinct categories.

Palynofacies charts for each studied well have been produced (Figures 5-6). Counts were undertaken on 200 particles. In this study 10 μm is considered as the minimum diameter for counting AOM as a single particle. The abundance terminology used in this study is: rare (0-5%), relatively common (6-10%), common (11-25%), abundant (26-50%) and dominant (>50%).

6.2 Palynofacies results and interpretation

In the studied sections of the Hawaz Formation palynofacies varies significantly between a lower and upper part. The lower part is characterized by abundant to dominant sphaeromorph acritarchs (35-60%). Acritarchs are rare to common, not representing more than 32%, and with moderate diversity. Chitinozoans are rare. Yellow-brown and dark-brown AOM occurs in varying abundances but is generally abundant. Cryptospores are common through this interval and plant tissue (Plate 6, figures 16-17) is rare to absent. The upper part is again characterized by the abundance of sphaeromorph acritarchs (50% or more). Acritarchs are rare to absent (not more than 5%), while chitinozoans are absent. However, the upper part is marked by the high abundance and diversity of cryptospores (20-44%).

Overall the palynofacies analysis is interpreted as reflecting upward shallowing towards more proximal marginal marine conditions. The lower part of the Hawaz Formation is interpreted as accumulated under condition of lower oxygenation based on the high abundance of AOM. This is considered to have been shallow inner shelf marine that shallows up sequence to marginal marine.

The above interpretation is consistent with studies by Romas et al. (2006) and De Gibert et al. (2011), based on lithology, sedimentology and trace fossils, who suggested that the entire Hawaz Formation was deposited in a shallow marine environment. Based on a sedimentological study of the Hawaz Formation, Anfray & Rubino (2003) suggested that the formation represents a major transgressive-regressive cycle. This interpretation is supported by our palynofacies analysis. Vecoli (1999) and Vecoli et al. (2003) obtained very similar palynological and palynofacies/palaeoenvironmental results for late Arenig-early Llanvirn sequences from the Hassi- R'Mel area of north-central Algeria (Well N1 2) and the northern Rhadames Basin of southern Tunisia (Wells St1, Sn1) and northwest Libya (Well A1-70). These sequences correlate in part with the Hawaz Formation based on the biostratigraphical data reported herein. They recorded a major transgression event in the late Arenig-early Llanvirn followed by a regression. This occurred in an open marine, offshore setting in southern Tunisia but more proximal marine conditions in north-central Algeria.

7. Palaeobotanical significance of the cryptospore assemblage

Cryptospores are interpreted as the dispersed spores of the earliest land plants (e.g. Wellman et al. 2013). Currently the oldest known cryptospore assemblage is from the Middle Ordovician (Dapingian) of Argentina (Rubinstein et al. 2010). However, cryptospores have only rarely been reported from the Middle Ordovician (Dapingian to Darriwilian) with other occurrences from Saudi Arabia (Strother et al. 1996; Le Herissé et al. 2007; Strother et al. 2015; Steemans et al. 2017) and the Czech Republic (Vavrdova 1984). Consequently this paper provides a very rare report of a very early cryptospore assemblage. Interestingly, all of the previous reports of cryptospores from the Middle Ordovician are also from Gondwana and PeriGondwana supporting ideas that land plants may have evolved on this continent (Wellman 2010). In light of the great age of the cryptospore assemblage described herein, the presence of dispersed fragments of cuticle (Plate 6, figures 17-18) and a cryptospore cluster (?sporangial contents) (Plate 6, figure 19) is of particular interest.

8. Conclusions

Palynological assemblages from the Hawaz Formation from the Murzuq Basin, southwest Libya are dominated by sphaeromorphs but also include rare but diverse acritarchs, rare chitinozoans, and relatively abundant cryptospores. The acritarch and chitinozoa assemblage enables biostratigraphical age dating and indicates a Mid Ordovician, most likely mid Darriwilian (Llanvirn), age. The cryptospore assemblages support this age designation but do not allow refinement of it. The age assignment enables correlation with other sequences in northern Gondwana. Based on palynofacies analysis the depositional environment of the Hawaz Formation is interpreted as shallowing upward from nearshore marine inner shelf to marginal marine. The cryptospore assemblage is a very rare example from the Middle Ordovician.

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Plate descriptions

Plate 1. Photomicrographs of acritarchs. 1. Ampullula suetica, Well-A28i-NC186, 4611 ft., D38/4, scale bar = 20µm. 2. Ampullula suetica,Well-A28i-NC186, 4611 ft., D38/4, scale bar = 10µm. 3. Baltisphaeridium cf. klabavense, Well-A28i-NC186, 4708 ft., V41/2, scale bar = 20µm. 4. Baltisphaeridium cf. klabavense, Well-A28i-NC186, 4708 ft., V41/2, scale bar = 10µm. 5. Cymatiosphaera sp. A, Well- A28i-NC186, 4708 ft., U27/4, scale bar = 10 µm. 6. Cymatiosphaera sp. A, Well- A28i-NC186, 4633 ft., Y39/1, scale bar = 10 µm. 7. Cymatiosphaera sp. B, Well- A28i-NC186, 4604 ft., U40/3, scale bar = 10 µm. 8. Dictyotidium sp. A, Well A28i-NC186, 4611 ft., P39/3, scale bar = 10µm. 9. Elektoriskos sp. A, Well A28i-NC186, 4715 ft., R33/4, scale bar = 10µm. 10. Frankea breviuscula, Well A28i-NC186, 4706 ft., S25, scale bar = 5µm.

Plate 2. Photomicrographs of acritarchs. 1. Frankea longiuscula?, Well A28i-NC186, 4708 ft., T36/2, scale bar =20µm. 2. Frankea longiuscula?,Well A28i-NC186, 4708 ft., G23/1, scale bar =20µm. 3. Frankea hamata, Well-H2-NC186, 4870 ft.T42, scale bar = 10µm. 4. Frankea sp. A, Well-H2-NC186, 4870 ft., U35, scale bar = 10µm. 5. Helosphaeridium? sp. A, Well A28i-NC186, 4715 ft., W50, scale bar = 10 µm. 6. Leiofusa cf. fusiformis, Well A28i-NC186, 4715 ft., T25, scale bar = 10 µm. 7. Leiosphaeridia spp.,Well A28i-NC186, 4723 ft., E40, scale bar = 10µm. 8. Lophosphaeridium cf. fuscipetiolatum, Well A28i-NC186, 4708 ft., O38/3/1, scale bar = 20µm. 9. Micrhystridium cf. equispinosum, Well-H2-NC186, 4870 ft., R52, scale bar = 10µm. 10. Pirea? Sp. A, Well A28i-NC186, 4708 ft., Q43/3, scale bar = 10 µm. 11. Poikilofusa cf. ciliaris, Well A28i-NC186, 4708 ft., L31/3, scale bar = 20 µm.

Plate 3. 1. Pterospermella colbathii, Well A28i-NC186, 4633 ft., R42, scale bar = 10µm. 2. Pterospermella colbathii, Well A28i-NC186, 4715 ft., O53/4, scale bar = 10 µm. 3. Pterospermella sp. A, Well A28i-NC186, 4725 ft., J36/1, scale bar =10 µm.. 4. Liliosphaeridium? sp. A, Well A28i-NC186, 4708 ft., N32/2, scale bar = 10 µm. 5. Comasphaeridium cf. solare, Well H2-NC186, 5000 ft., N47/1, scale bar = 5 µm. 6. Stelliferidium philippotii, Well H2-NC186, 5000 ft., S30/2, scale bar = 10 µm. 7. Stelliferidium strailutum, Well D1-200, 5600-5650 ft., S42, scale bar = 10 µm. 8. Stelliferidium stelligerum, Well A28i-NC186, 4708 ft., C35, scale bar = 10µm.

Plate 4. 1. Stelliferidium simplex, Well A28i-NC186, 4708 ft., O32, scale bar = 10µm. 2. Stelliferidium simplex, Well A28i-NC186, 4706 ft., O32, scale bar = 10µm. 3. Stellechinatum spp., Well A28i-NC186, 4708 ft., K43, scale bar = 5µm. 4. Stellechinatum spp., Well A28i-NC186, 4715 ft., L43/4, scale bar = 10µm. 5. Uncinisphaera fusticula, Well A28i-NC186, 4708 ft., T30/4, scale bar = 10µm. 6. Uncinisphaera fusticula, Well A28i-NC186, 4708 ft., T30/4, scale bar = 5µm. 7. Veryhachium cf. lairdii, Well A28i-NC186, 4715 ft., V35, scale bar = 5µm.

Plate 5. 1. Veryhachium trispinosum group, Well A28i-NC186, 4518 ft., K31/1, scale bar = 10µm. 2. Virgatasporites cf. rudi, A28i-NC186, 4715 ft., R43, scale bar = 5µm. 3. Belonechitina micracantha, Well-H2-NC186, 4833 ft., scale bar = 25µm. 4. Conochitina sp. A, Well-H2-NC186, 4950 ft., scale bar = 48µm. 5. Details of 4, showing ornamentation, scale bar = 15µm. 6. Euconochitina brevis, Well-H2-NC186, 4950 ft., S50/3, scale bar = 34µm. 7. Siphonochitina formosa, Well H2-NC186, 4950 ft., scale bar = 35µm. 8. Velatachitina sp. A, Well-H2-NC186, 4950 ft., scale bar = 40 µm. 9. AOM (dark brown), A28i-NC186, 4796ft, T26/2. 10. AOM (yellowish brown), A28i-NC186, 4796ft, S23/1.

Plate 6. 1. Chelinohilates maculatus, Well A28i-NC186, 4604 ft., C37, scale bar = 15 µm. 2. Dyadospora murusdensa, Well A28i-NC186, 4604 ft., R26/4, scale bar = 10µm. 3. Hispanaediscus? verrucatus, Well A28i-NC186, 4633ft., R22/3, scale bar = 10µm. 4. Hispanaediscus cf. wenlockensis, Well A28i-NC186, 4604 ft., P37/1, scale bar = 13 µm. 5. Laevolancis chibrikovae, Well A28i-NC186, 4604 ft., M34/1, scale bar = 10µm. 6. Laevolancis divellomedium, WellA28i-NC186, 4715 ft., J33, scale bar = 15µm. 7. Pseudodyadospora laevigata, Well A28i-NC186, 4604 ft., W28/2, scale bar = 10µm. 8. Pseudodyadospora petasus, Well A28i-NC186, 4604 ft., M23/4, scale bar = 10µm. 9. Rimosotetras problematica, Well A28i-NC186, 4708 ft., S40/1, scale bar = 10µm. 10. Sphaerasaccus glabellus, Well A28i-NC186, 4604 ft., T37/1, scale bar = 7µm. 11. Tetrahedraletes medinensis, Well A28i-NC186, 4604 ft., U38/4, scale bar = 7µm. 12. Tetrad sp. A, Well H2-NC186, 4833 ft., Q34/3, scale bar = 10µm. 13. Velatiteras laevigata, Well A28i-NC186, 4604 ft., C40, scale bar = 10 µm. 14. Tetraplanarisporites laevigatus, Well A28i-NC186, 4611 ft., N36/2, scale bar = 10µm. 15. Genus A sp. A Steemans et al. 2000, Well A28i-NC186, 4604 ft., D26, scale bar = 12.5µm. 16. Microgranulate monad, Well A28i-NC186, 4604 ft., C40, scale bar = 5µm. 17. Cuticle-like sheet, A28i-NC186, 4706 ft., N32/2. 18. Cuticle-like sheet, H2-NC186, 4604 ft., C45. 19. Cluster of monads.

PLATE 1

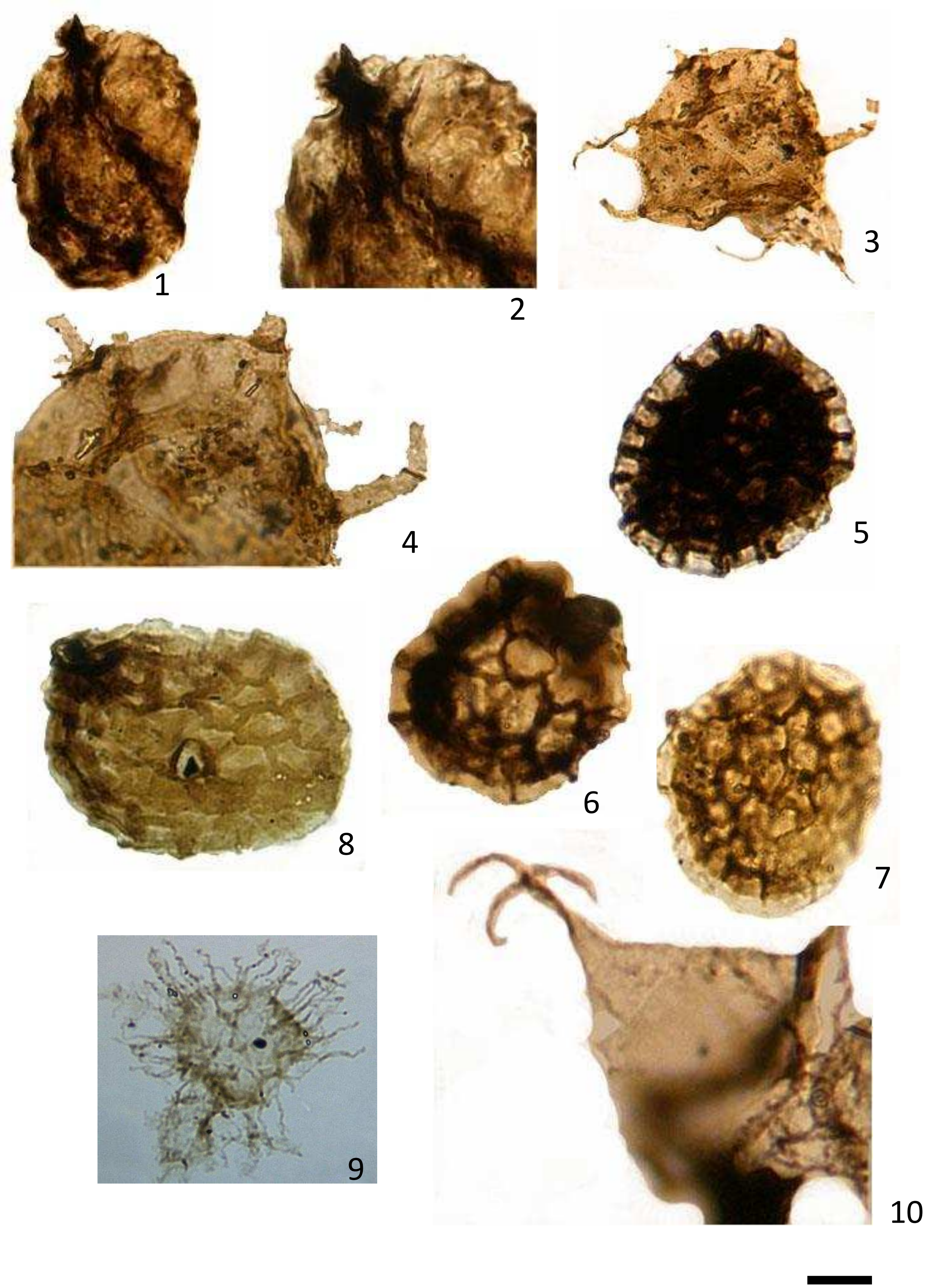
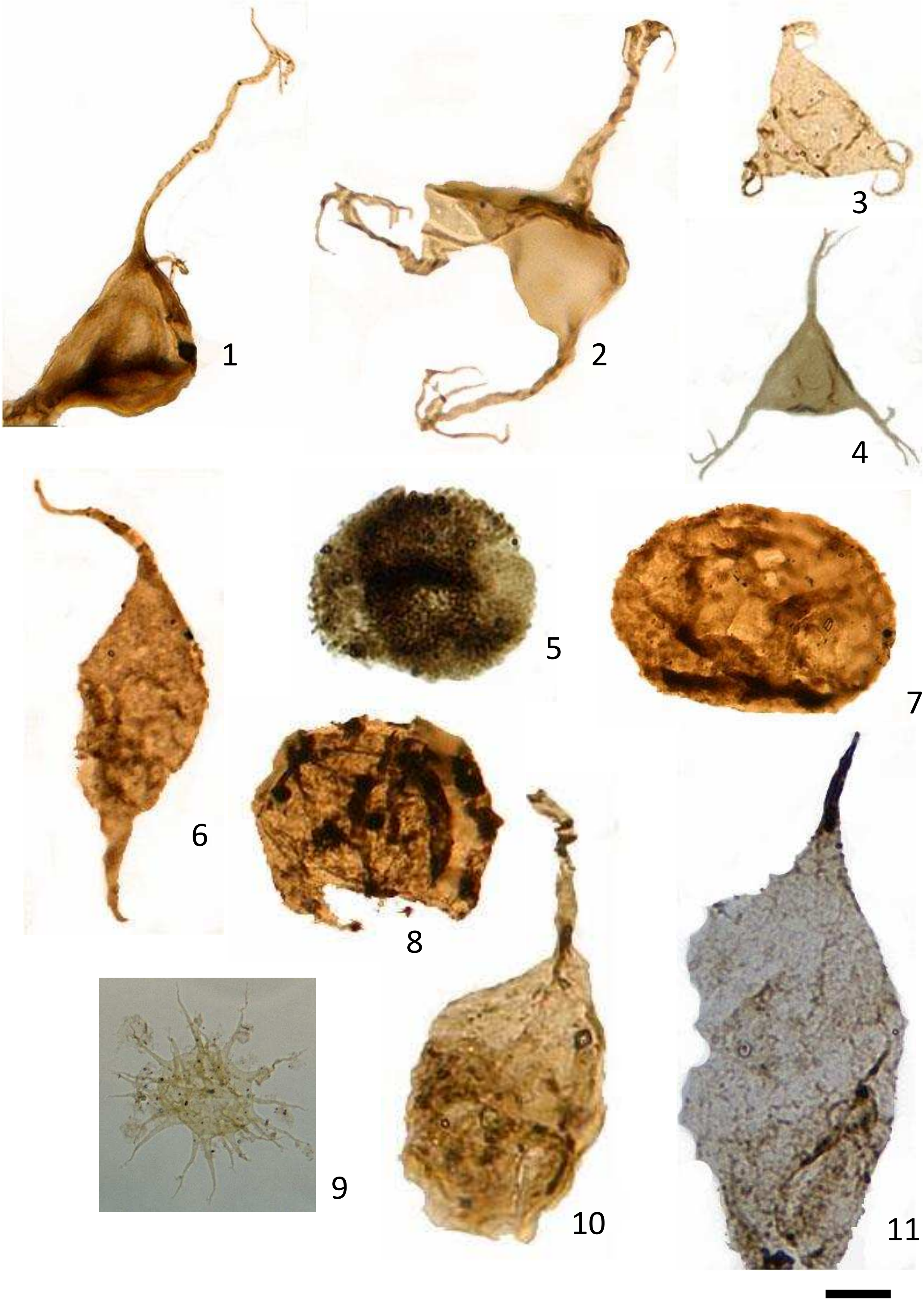


PLATE 2



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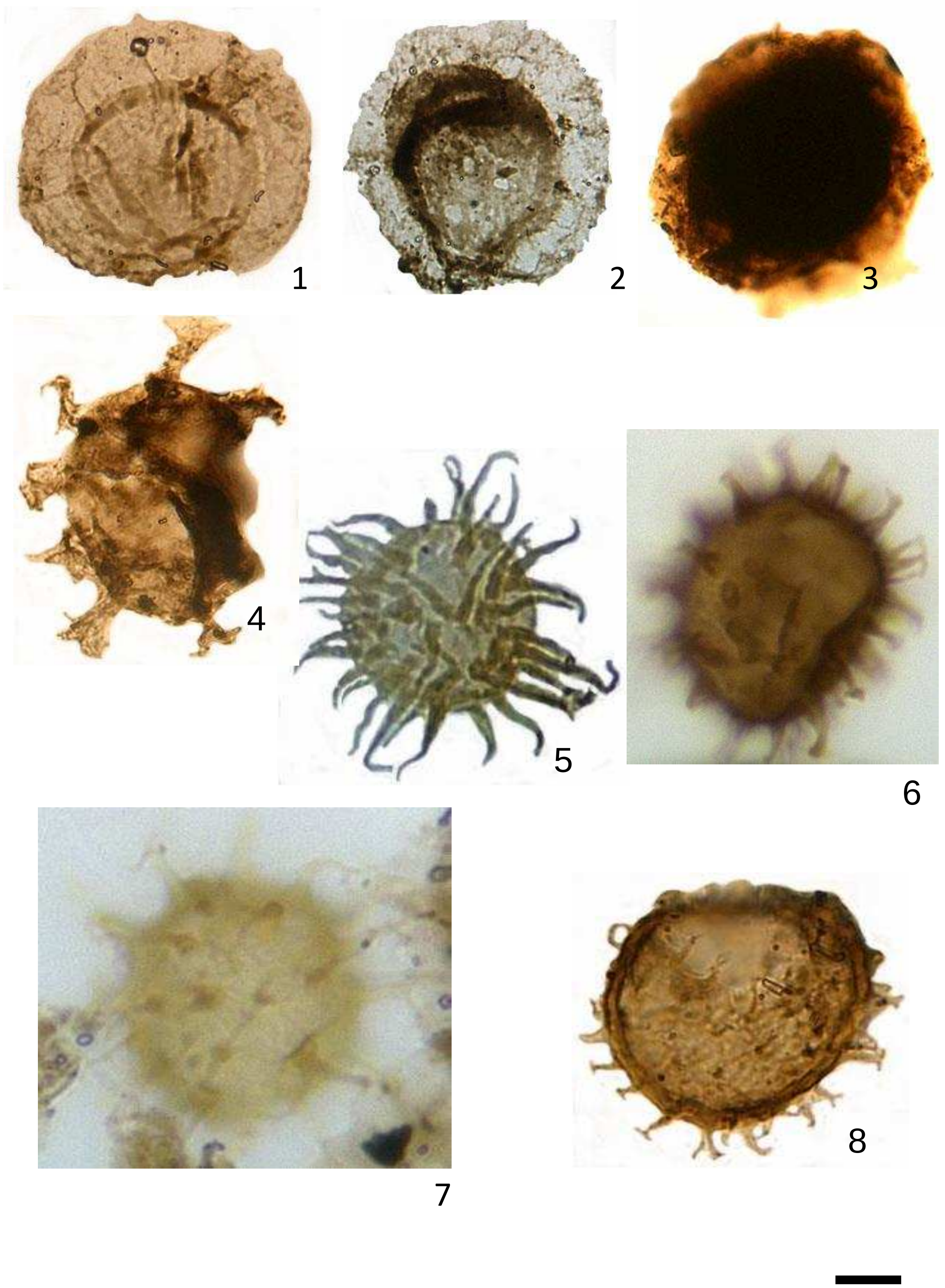

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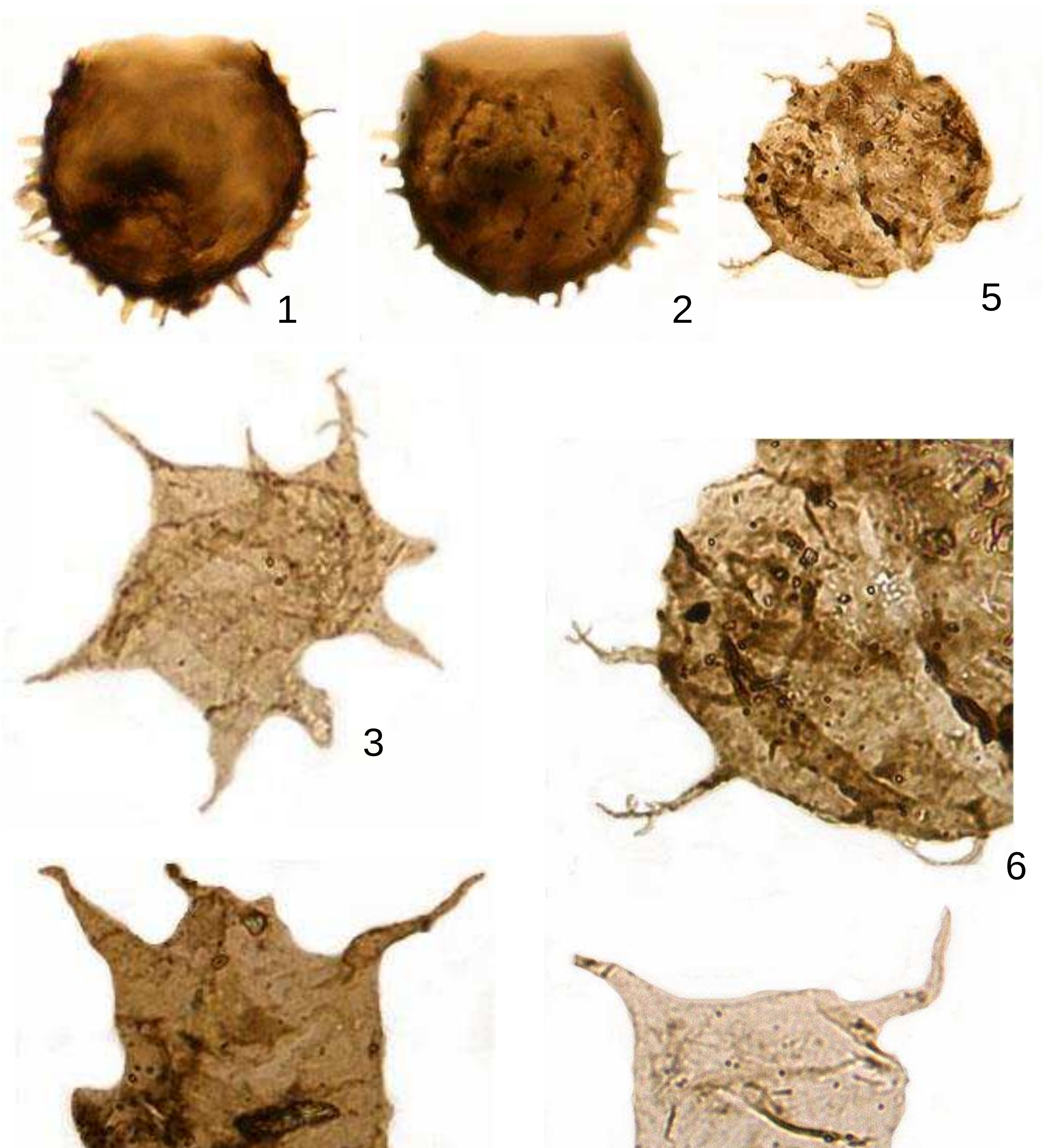

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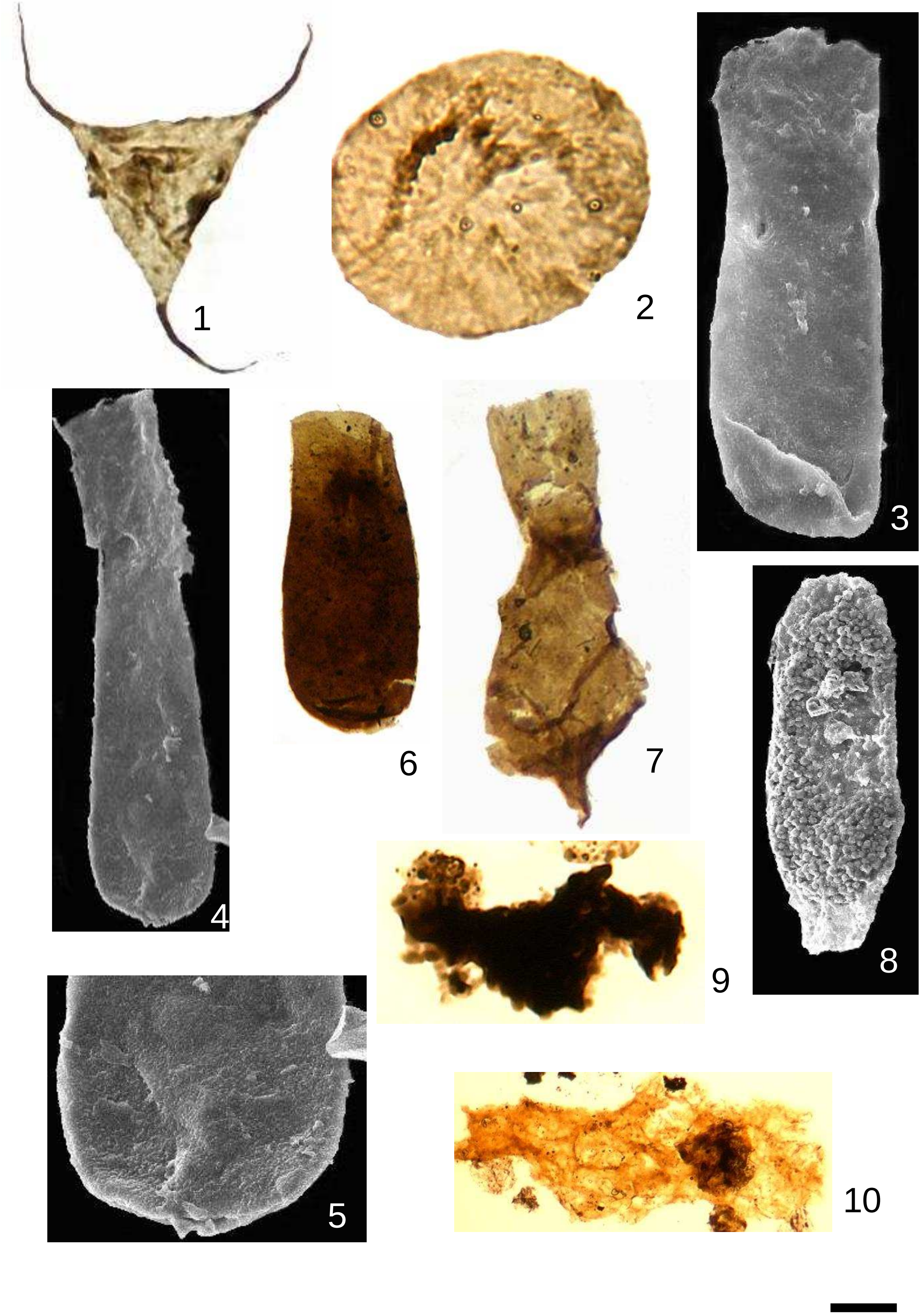
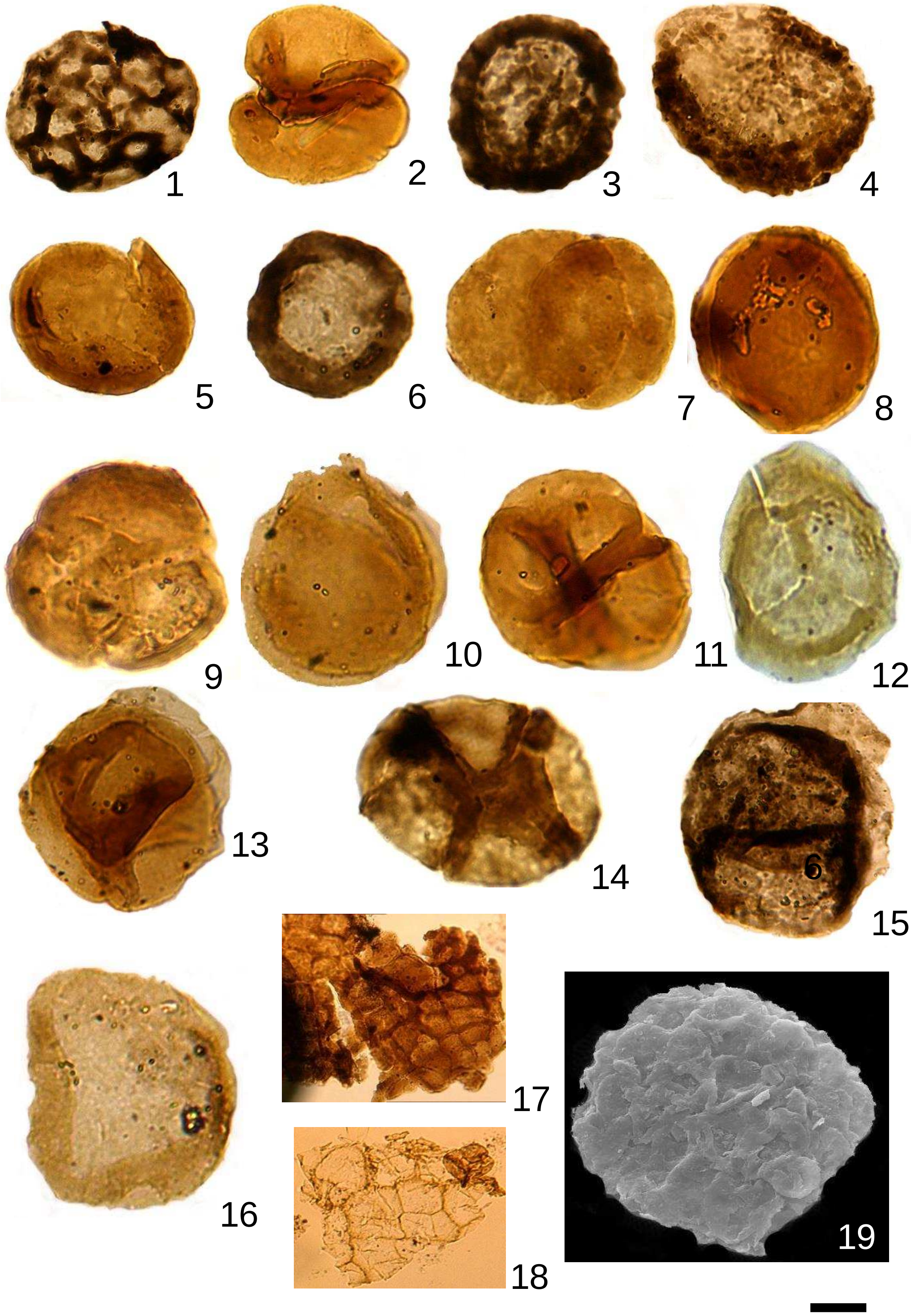


PLATE 6



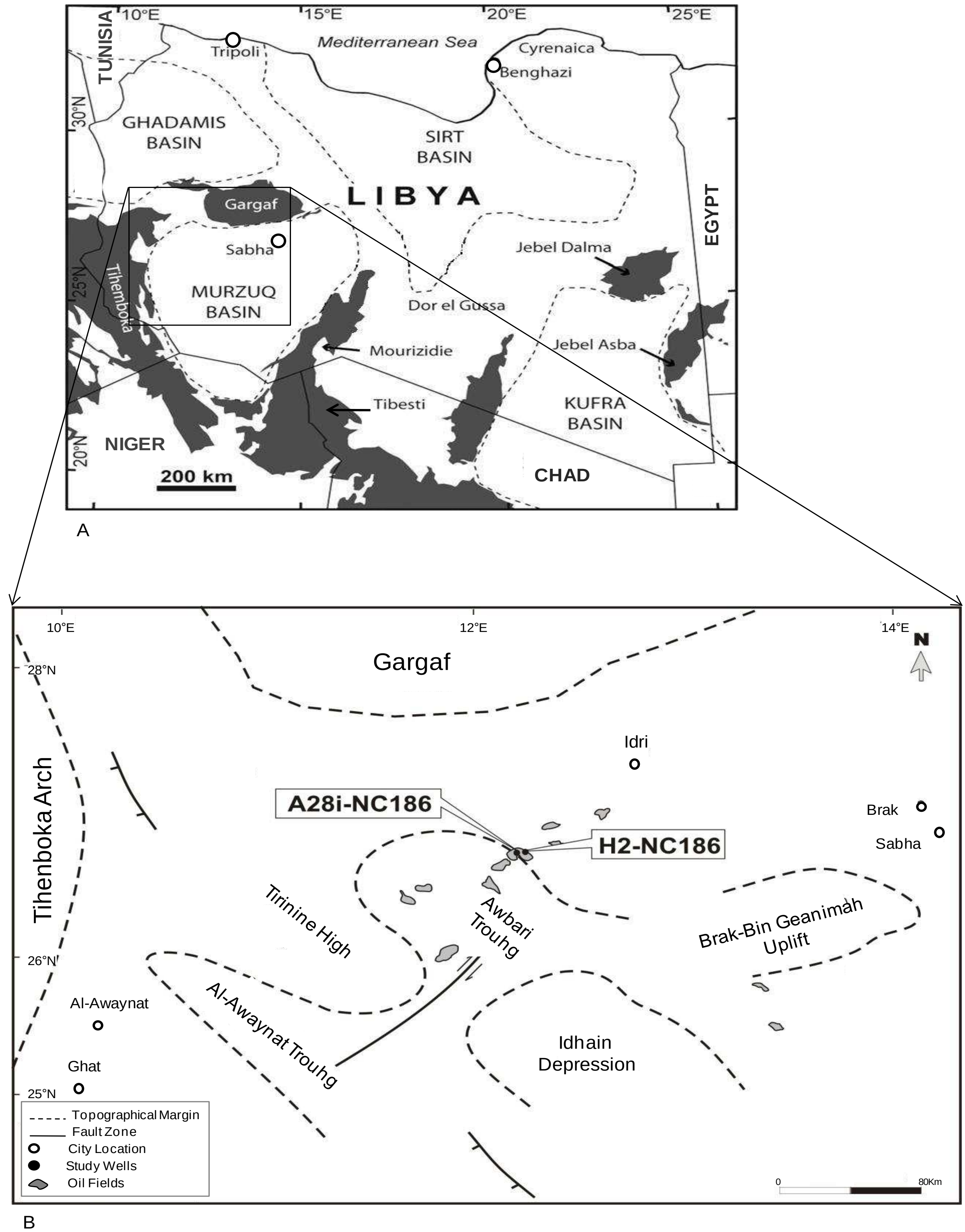


Figure 1 A. Map of Libyan Palaeozoic sedimentary basins. B. Map of the Murzuq Basin, southwest Libya showing tectonic elements and the location of the studied boreholes (after Echikh & Sola 2000).

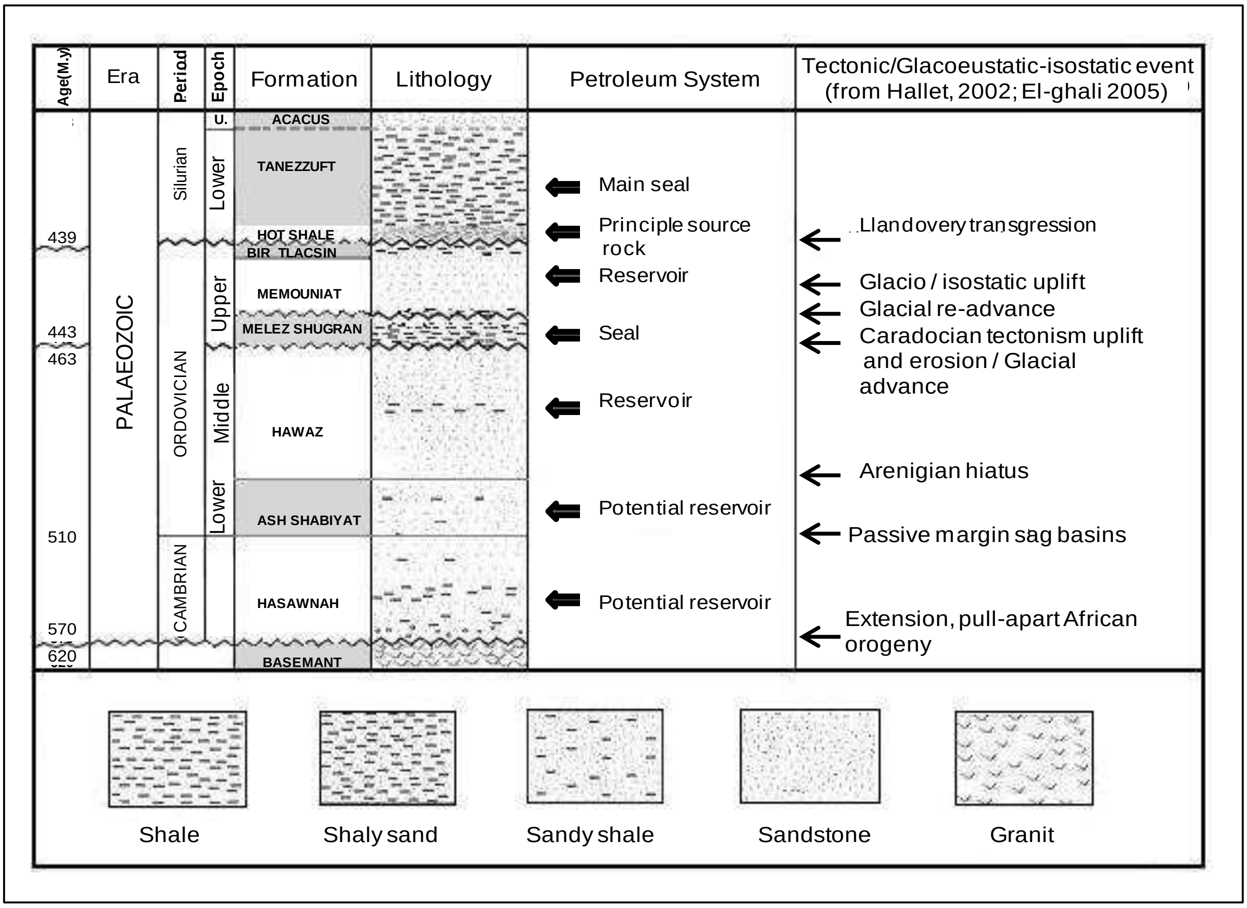


Figure 2. Simplified lithostratigraphic framework of the Cambrian-Silurian sequence in Murzuq Basin (after Hallet 2002; El-ghali 2005).

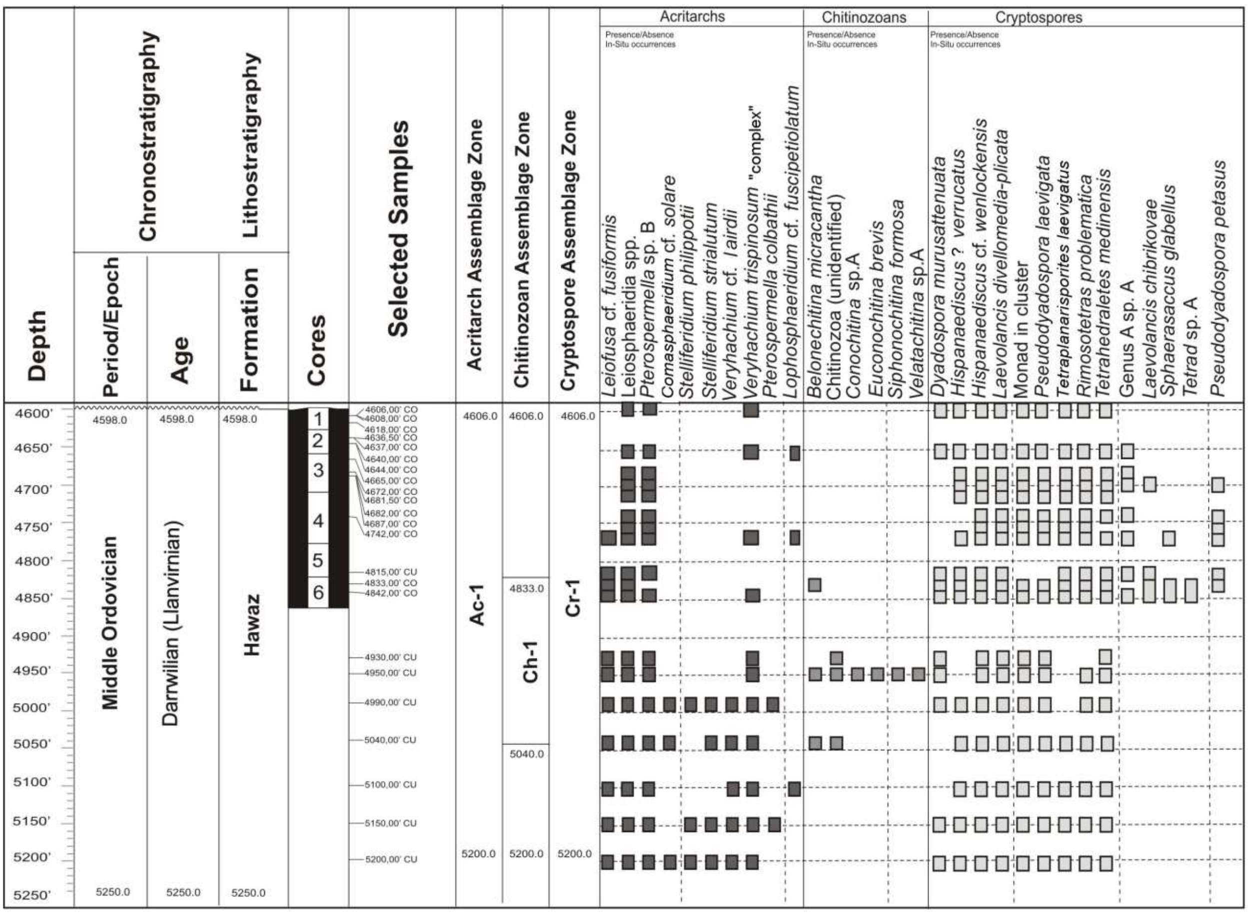


Figure 3. Distribution chart of palynomorphs recovered from Well H2- NC186, Murzuq Basin, southwest Libya.

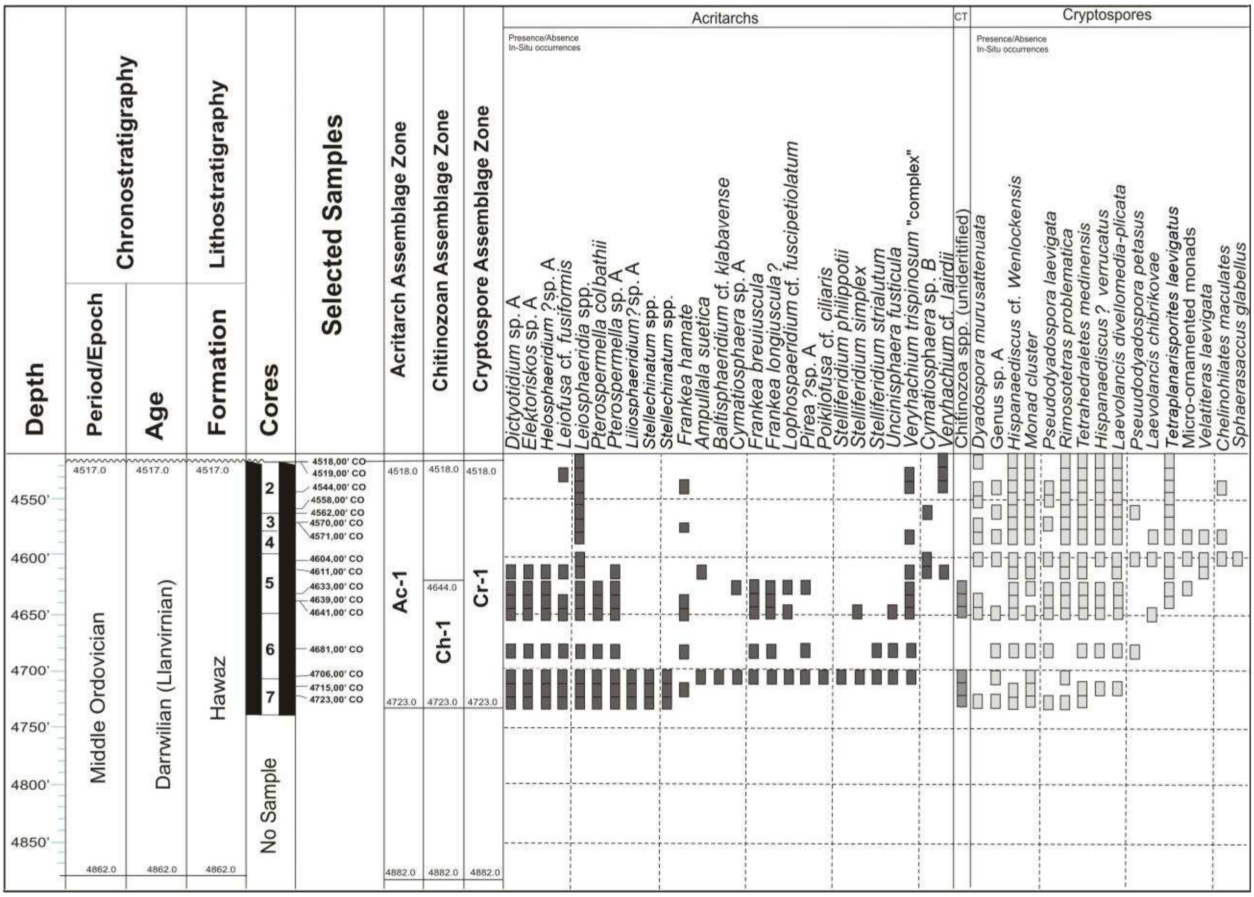


Figure 4. Distribution chart of palynomorphs recovered from Well A28i-NC186, Murzuq Basin, southwest Libya.

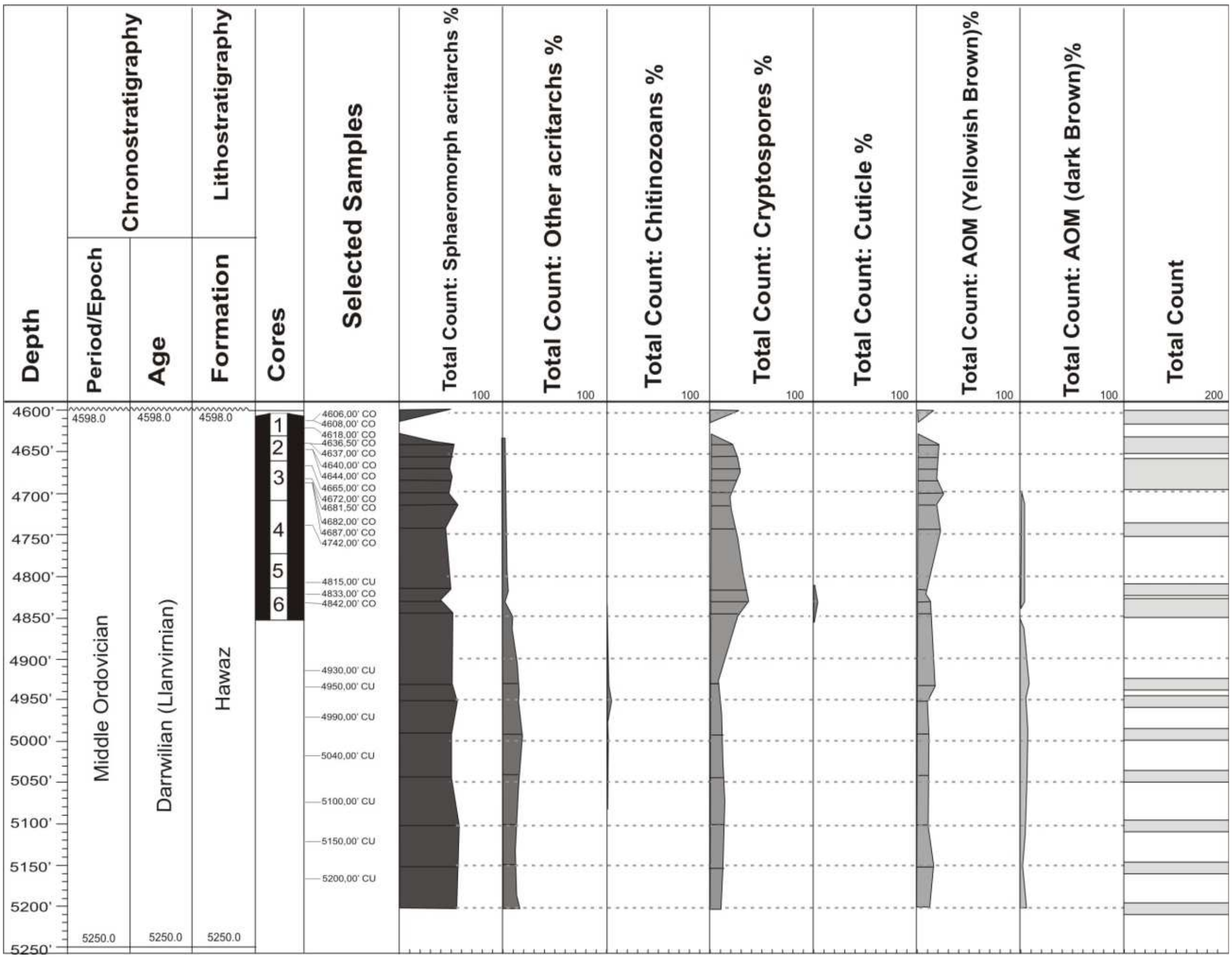


Figure 5. Palynofacies chart of Well H2-NC186, Murzuq Basin, southwest Libya.

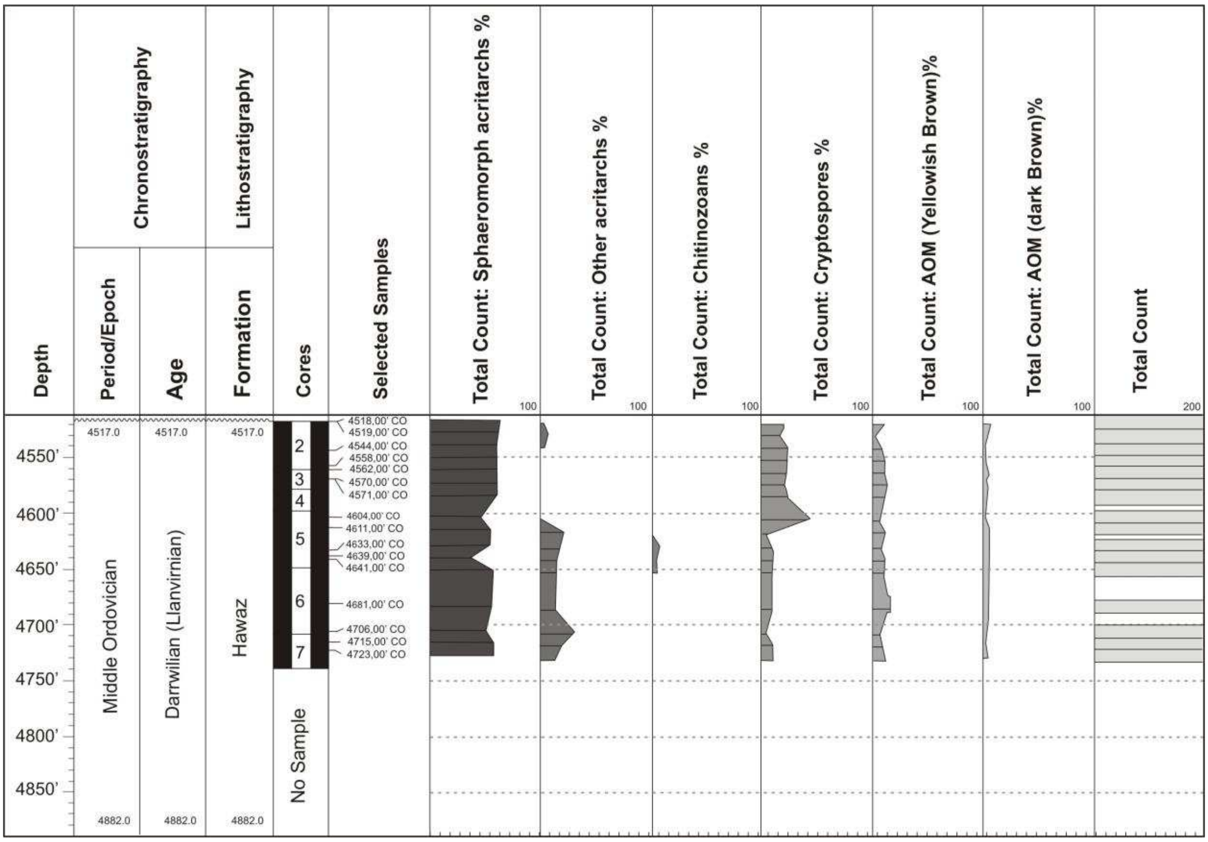


Figure 6. Palynofacies chart of Well A28i-NC186, Murzuq Basin, southwest Libya.