

Calcimicrobe tubules in uppermost Jurassic Arab-A carbonates of Saudi Arabia

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ABSTRACT

Uppermost Jurassic carbonates from the Arab-A Member of the Arab Formation in the subsurface of eastern Saudi Arabia reveal hollow, intertwined, locally bifurcating, microtubules consisting of a chain-like, uniserial series of inaperturate, stacked, concavo-convex crescentic chambers tentatively assigned to *Gahkumella* sp. Previously confined to the Oxfordian of North America, and possibly the Lower Cretaceous of Oman, this is believed to be the first observation of such forms in uppermost Jurassic carbonates. The carbonates consist of a lower, transgressive, ooid-foraminiferal lithofacies and an upper, regressive, stromatolite-ostracod lithofacies of which the microtubules are developed in the latter. Comparison of these structures with fossil and Recent cyanobacterial microborings and Oxfordian calcimicrobial tube-like forms suggests probable cyanobacterial affinity. Despite their very limited stratigraphic extent, they may contribute to improving mouldic microporosity of the Arab-A carbonate reservoir.

INTRODUCTION

Qatif field, located in eastern Saudi Arabia, contains stacked Jurassic carbonates that are prolific hydrocarbon-bearing reservoirs. The Arab Formation of Saudi Arabia is of Late Jurassic, Kimmeridgian to Tithonian age (Sharland et al., 2001; Hughes, 2004) and consists of four carbonate units that have been designated member suffixes D, C, B and A in ascending stratigraphic order (Powers, 1968; Wilson, 1985; Moore, 2001, his Figure 6.44; Lindsay et al., 2006). Each of the carbonate units of the Arab Formation is separated from the next by beds of anhydrite, termed the D, C and B anhydrite with respect to the underlying Arab-D, Arab-C and Arab-B carbonate members, except for the anhydrite that overlies the Arab-A carbonate which is called the Hith Formation (Figures 1 and 2).

The Arab-A carbonate in the study well consists of a 34 ft thick succession of carbonates that overlies the Arab-B anhydrite and is overlain by the Hith anhydrite. During routine, semi-quantitative, micropalaeontological analysis of thin sections prepared from core plug samples from the Arab-A carbonates, a single sample displayed a cavity containing a collection of enigmatic uniserial, chambered, hollow, intertwined, bead-like, vermiform, tubular microfossil moulds. Dense, grey, dendroidal masses of microgranular thrombolite and intra-thrombolite cavities characterise the core from where the sample was cut (Figure 3). Microstromatolitic structures are present within the dendroid framework below the chambered microtubular forms at a level sampled by core-plug 10 (Figure 4h), whereas microgranules are typical of the section above the zone of interest (Figure 4a). The presence of blue-dyed epoxy resin, injected into the core plug during thin section preparation to display visible porosity, enhances the appearance of these forms (Figures 4b to 4g). Their unusual nature, and source of mouldic microporosity, is of hydrocarbon reservoir interest despite their apparent absence from the remaining part of this core. The chambered microtubules have not been named in formal publications, but they show similarity to early Proterozoic *Frutaxites* sp. in Canada (Hofman and Grotzinger, 1985), and closely resemble un-named, *Renalcis*-like cyanobacterial tubules of Oxfordian age from North America (Fischer et al., 2007) and Permian to Tithonian forms termed *Gahkumella huberti* from Iran and Spain respectively.

MORPHOLOGY

The structures are present as a concentration of hollow, possibly intertwined and not necessarily mutually supporting, gently and randomly curving, vermiform, chambered microtubules (Figures

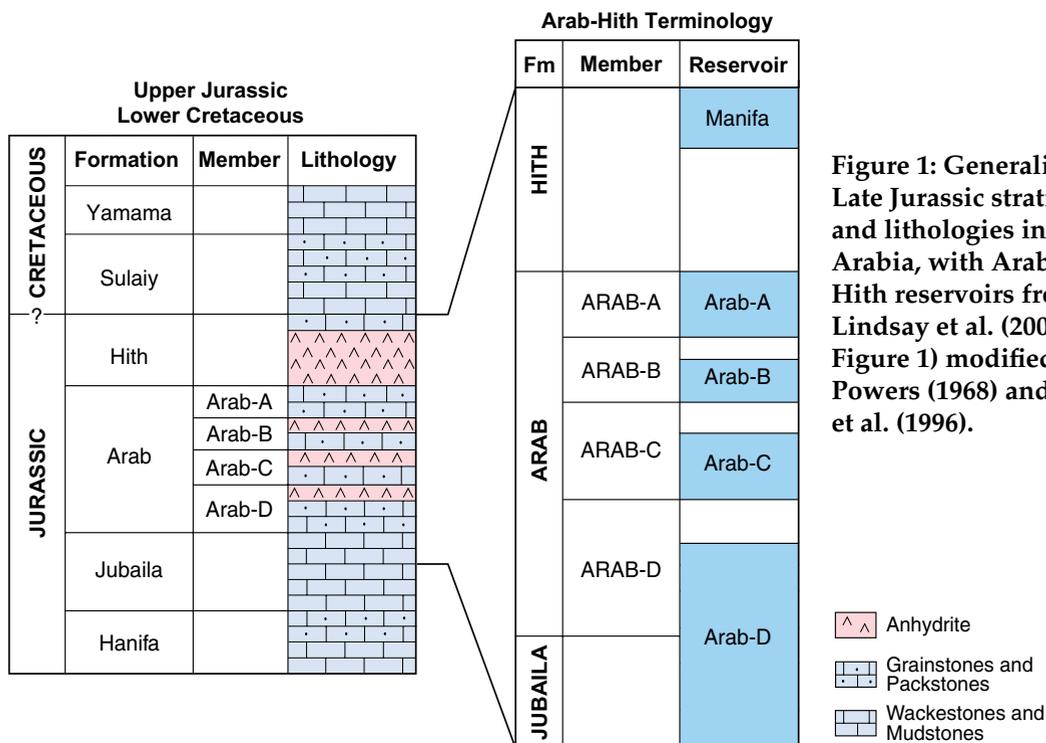


Figure 1: Generalized Late Jurassic stratigraphy and lithologies in Saudi Arabia, with Arab and Hith reservoirs from Lindsay et al. (2006, Figure 1) modified from Powers (1968) and Meyer et al. (1996).

4b to 4g). Maximum tubule length observed in the thin section is 300 μm , with a consistent width of 40 μm . There is no evidence to suggest that the diameters of the microtubules enlarge in any direction, but they do exhibit "Y-shaped" bifurcation (Figure 4g). The tubules are composite, being composed of a uniserial succession of stacked, chamber-like structures with chamber height of approximately 10 μm . Each crescentic chamber is convex on one side and concave on the opposite, in a manner typical of uniserial foraminiferal growth. Unlike most foraminifera, however, there is no aperture through which chambers could have communicated, although definite exclusion of foraminiferal affinity is impossible owing to rare records of inaperturate foraminifera (Nestell and Tolmacheva, 2004; Kaminski, 2004). Orientation of the tubules is reliant on the attitude of the convex side of the septae. The bifurcating nature of the tubule suggests that the curved septal face was convex outwards into the plane of growth (Figure 4g). A growth pattern with upward convex chamber surfaces is interpreted by Fischer et al. (2007), although examination of their figure, in which the stratigraphic top is indicated, reveals that these forms do not consistently display an upwards convex chambered succession (Figure 5).

BIOSTRATIGRAPHY

A Kimmeridgian to Tithonian age has been assigned to the Arab Formation, based on ammonite and foraminiferal evidence in the underlying carbonates of the Jubaila Formation, isotope and nannofossils data from the overlying Hith and Sulaiy formations respectively and regional sequences stratigraphy (Sharland et al., 2001; Hughes and Naji, 2009). Biostratigraphic age markers are absent from the Arab-A carbonates, but a sequence stratigraphic interpretation by Sharland et al. (2001) would place them between genetic stratigraphic sequences (GSS) 100 and 110, of Late Kimmeridgian to Late Tithonian age.

Tithonian coccoliths, including the Tithonian species *Conusphaera mexicana minor*, have been recovered from the lower Sulaiy Formation, in the absence of Cretaceous species (Osman Varol, personal communication). Vaslet et al. (1991) submitted a sample of anhydrite from Dahl Hith for oxygen ($\delta^{18}\text{O} = +13.3$) and sulphur ($\delta^{34}\text{S} = +13.3$), and state that these values fitted well within a Late Jurassic portion of the curve of Claypool et al. (1980). Biostratigraphic investigation of the Hith Formation in adjacent countries is also limited, but strontium isotope studies on samples from the Arab-A and Hith

anhydrite in Abu Dhabi (Azer and Peebles, 1998) provided Late Kimmeridgian and Early Tithonian ages, respectively. The Hith-equivalent Rayda Formation of Oman yields small ammonites belonging to Perisphinctidae of uppermost Tithonian age (Rousseau et al., 2005) and would support a Tithonian age for the equivalent Hith carbonates in Saudi Arabia.

AFFINITY

It is difficult to confidently assign a biological affinity to these forms based on morphology alone and although a cyanobacterial microbialite is concluded some of the other possibilities are here considered below.

Foraminifera

Although the stacked arrangement of the crescentic chambers resemble those of uniserial foraminifera, the lack of apertures between the “chambers” is evidence to probably preclude assignment to foraminifera, where apertures are mostly present.

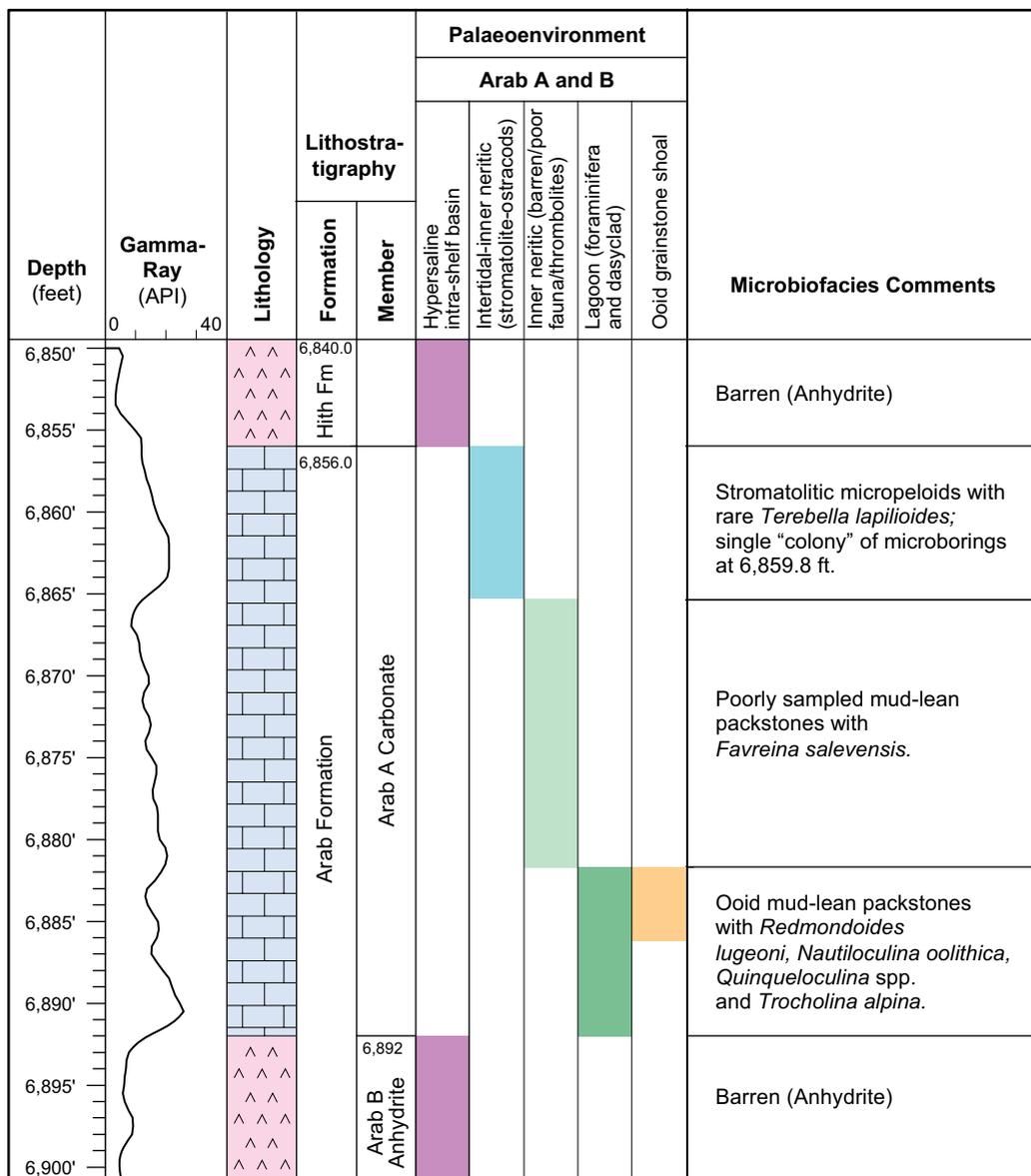
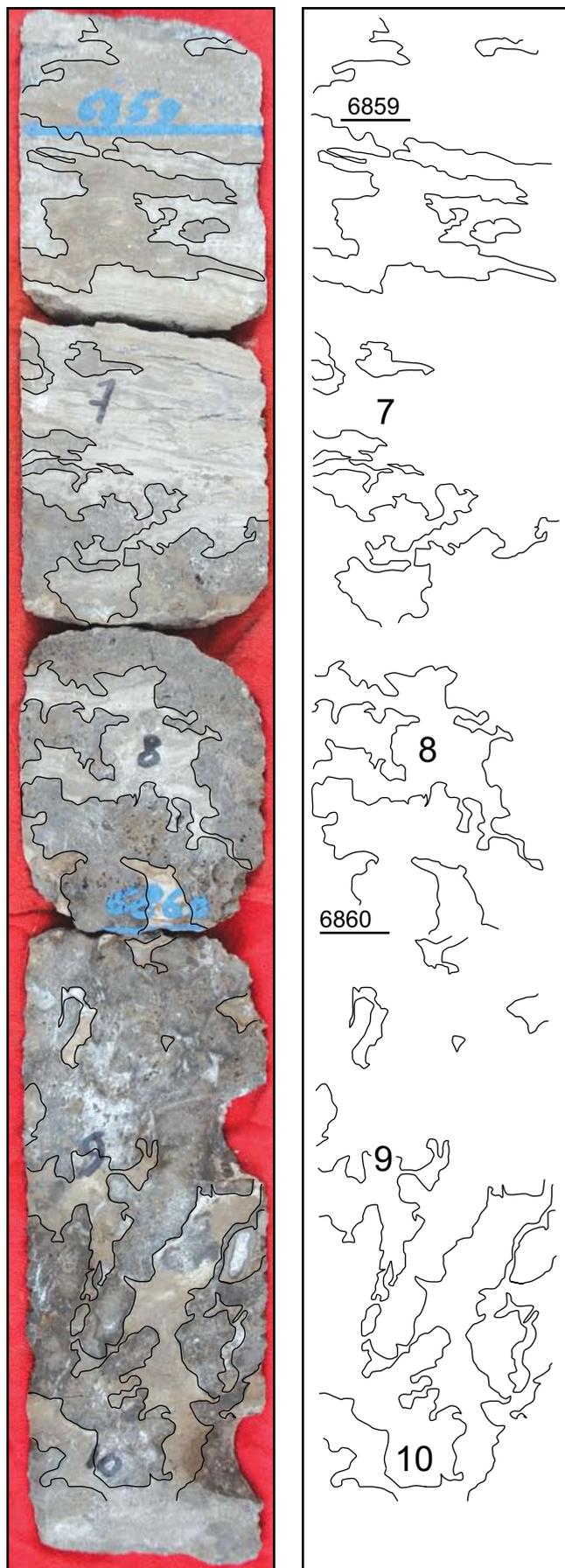


Figure 2: Diagrammatic depiction of the cored section of Arab-A Member in the studied well from Qatif field, Saudi Arabia, showing depth, gamma log, simplified lithology, lithostratigraphy, palaeoenvironmental interpretation and microbiofacies comments.



Chlorophytes

Forms resembling those observed in the present study compare morphologically with a form illustrated by Luperto Sinni (1979, see their Plate 3, Figure 7) and described as the chlorophyte *Cretacicladus minervini*. Other illustrations of this form by Luperto Sinni tend to more closely resemble vertical sections through stacked dasyclad thalli, and are not considered to represent the form here described.

Microburrows

Slight similarity of the structures to microspreite suggest the possibility that these forms could possibly represent microburrows, and would imply that they were made within soft, probably micritic sediment, prior to neomorphosis to calcite cement. A microburrow association is considered unlikely, however because the septae-like structures are convex outwards, and not inwards as their interpretation as microscopic spreite would necessitate (Seilacher, 2007). The presence of the chambered microtubules within cavities within the host rock would also preclude a boring origin, unless the burrowed sediment has been removed after lithification of the burrow. A microburrow origin is considered unlikely.

Microborings

In support of a microboring origin Königshof and Glaub (2004) illustrate cyanobacteria microborings from Palaeozoic condonts in which the species *Fasciculus dactylus* has a uniserial, multichambered and vermiform appearance, and are categorised as "Microcavity Type 2." Such forms are interpreted to have developed under conditions dominated by cyanobacteria, and to represent vertically oriented microborings. If these microborings did indeed bore into rock substrates, then they could be considered as euendoliths,

Figure 3: Section of core from the studied well in Qatif field showing darker patches of cemented, microgranular dendroidal thombolite in the Arab-A carbonates, between 6,859 and 6,861 feet, with location of core plugs #7 to #10.

as defined by Golubic et al. (1984). Chambered, compartmented filamentous cyanobacterial boring traces include those attributed to *Solentia* sp. within Recent *Archaias* foraminiferal tests (Reid and Macintyre, 2000, their Figures 1A-D; Plates 2 and 3), *Matteia conchicola* within Recent clam shells (Chacon et al., 2006, their Figure 1 G-H) and *Hyella caespitosa* within Recent and Pleistocene ooids (Harris et al., 1979). These Recent cyanobacterial microborings all display a segmented nature, of which the terminal active surface of the microbore is convex outwards. The stack of convex-outwards septae in the Qatif examples, if they can be attributed to a boring origin, could possibly be explained as successive pulses of cyanobacterial activity, with each pulse leaving an organic trace. Controls on the periodicity of each growth phase are unknown, but could reflect a response to salinity, nutrient or temperature variations. A microboring origin is considered unlikely.

Biom mineralised Chambered Microtubules of Cyanobacterial Origin

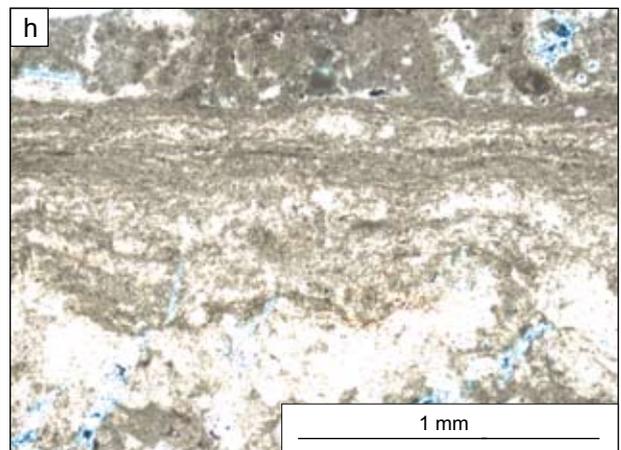
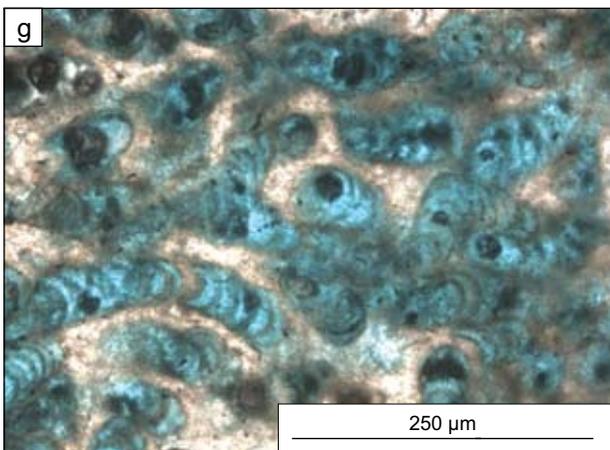
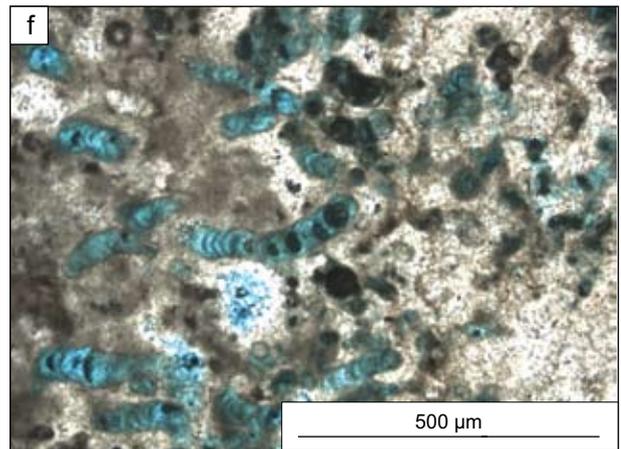
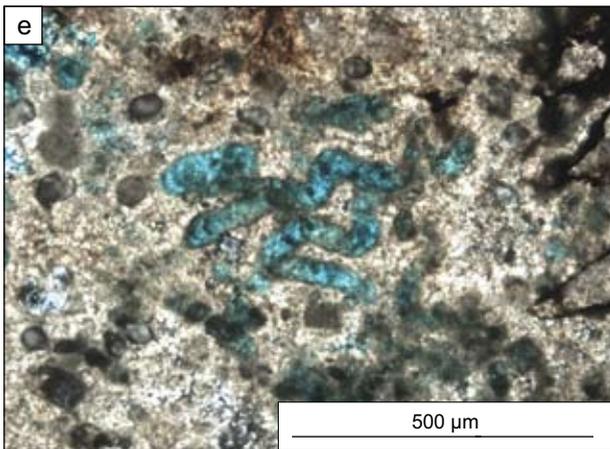
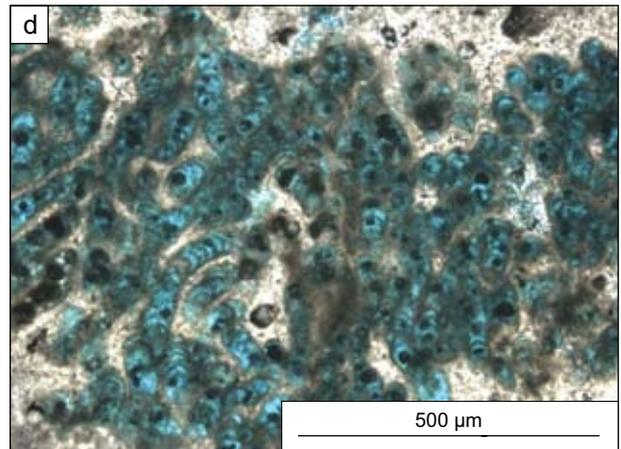
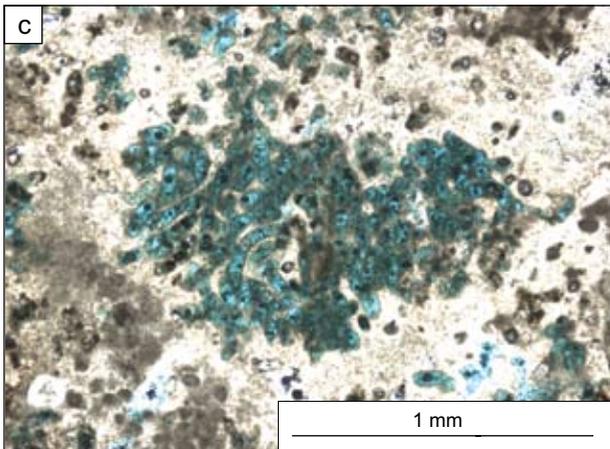
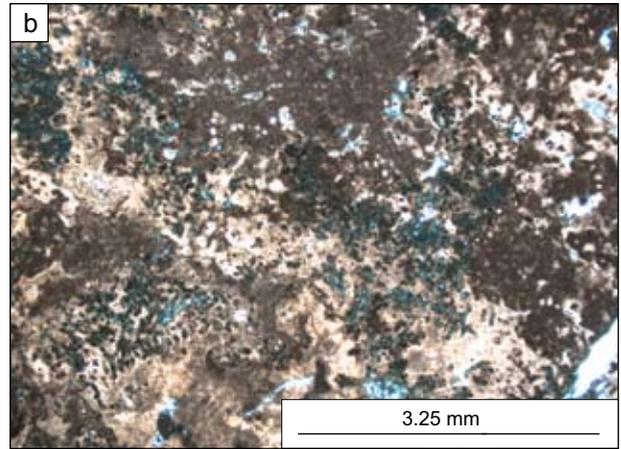
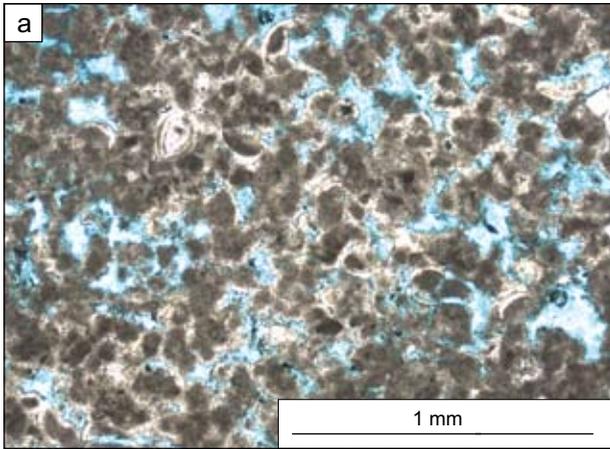
Un-named calcareous tubular micro-organisms described from the Oxfordian Smackover Formation of Alabama by Kopaska-Merkel and Schmid (1999) and Fisher et al. (2007) more closely resemble the forms here described than any other published records available to the author. The form also closely resembles the *incertae sedis Gahkumella huberi*, recorded from the Permian of Iran (Zaninetti, 1978) and from the Tithonian of Spain (Granier, 1986) where they are associated with *Thaumatoporella parvovesiculifera* and *Clypeina* (Granier, <http://brunogranier.free.fr/fr/part20.html>).

Proterozoic convexly laminated microscopic unbranched or branched columns called *Frutexitis* sp., in association with stromatolites (Hofmann and Grotzinger, 1985), show some similarity to the microstructures here described, and have been compared with thick-sheathed scytonematacean cyanobacteria (Walter and Awramik, 1979). This association is not agreed upon by Hofmann and Grotzinger (1985) who suggest a rivularian affinity if of cyanobacterial origin, or of eubacterial or physiochemical accretion, of which they seem to prefer microbially-mediated coprecipitation of the component minerals aragonite and iron oxide.

The close morphological similarity of the calcareous microtubules to forms interpreted to represent calcified cyanobacterial forms, in the absence of additional features of identification, would suggest that they may represent the product of non-enzymatic biomineralisation as described by Webb (2001). The Smackover micritic tubules are embedded in radial fibrous calcium carbonate cement and are cylindrical, sparsely branched with "Y-shaped" junctions and average 42 to 57 μm in diameter and up to 600 μm long. In his discussion on cyanobacterial morphology, Flugel (2004) omits reference to segmented tubules, and the classification scheme for calcified cyanobacteria by Riding (1991) also fails to include forms here described. There is some resemblance to the chains of coccoid bacteria except that such forms have linear inter-coccal sutures, and are generally inflated to globular shaped.

Fischer et al. (2007) describe how intertwined tubules in microhermal nodules can be constructed by microbial growth under environmentally restricted conditions within cavities formed by early lithifying microbialites. Reduced circulation and elevated pH values permitted colonisation by non-photosynthetic and non-phototactic microorganisms, the metabolic processes of which are considered to elevate the local environment to a supersaturation level leading to carbonate precipitation, in the mode described by Knorre and Krumbein (2000). A coating of microcrystalline calcite surrounds the clustered digitate and branching chambered microfossils illustrated by Fischer et al. (2007) that closely resemble the dark, dense microtubule periphery of the forms here described. They are believed to have grown within cavities created by accretionary microbialites in the Oxfordian Novillo Formation of Mexico, in which the forms are up to 400 μm long, with the partitions 15 to 40 μm apart, and with widths of between 25 and 100 μm .

An important difference between these microstructures in the Arab-A of Qatif and published forms is the lack of cement within the former. Dendroidal thrombolite from the Smackover Formation, as illustrated by Mancini et al. (2004, their Figure 3C) is here illustrated in Figure 5, and closely resembles those in the Arab-A carbonates of Qatif (Figure 3). Successive "chambers" are considered by Pratt (1984) to have been formed by succeeding colonies of coccoid "blue-green" algae, or cyanobacteria, with calcification being an early process leading to "diagenesis taxa." The coccoid unicell *Polybessarus* from Neoproterozoic peritidal micrites displays a growth pattern with chamberlike terminations



that are, in contrast to the forms discussed here, concave in the direction of growth (Kah and Knoll, 1996) thus adding further confusion to the precise identification of the causatory process.

The tubules described by Fischer et al. (2007) consist of a linear series of convex-upward septae spaced 14 to 42 μm apart and have been compared to the extinct cyanobacterial form *Renalcis*. They are, however, different from the globular morphology of *Renalcis* and the unsegmented tubules of *Epiphyton*. Riding (written communication) has pointed out, however, that “the main difference is that *Renalcis* usually does not form such long series of chambers”. Some *Renalcis*, especially *Izhella* which is most common in the Late Devonian, have well-defined dark walls that resemble crescent moons in section with somewhat like those described by Fischer et al. (2007) although *Izhella*'s walls also contain distinctive clefts rather like V-shaped cracks in the inner surfaces. These tubules are considered to most closely resemble the chambered microtubules from the Arab-A carbonate.

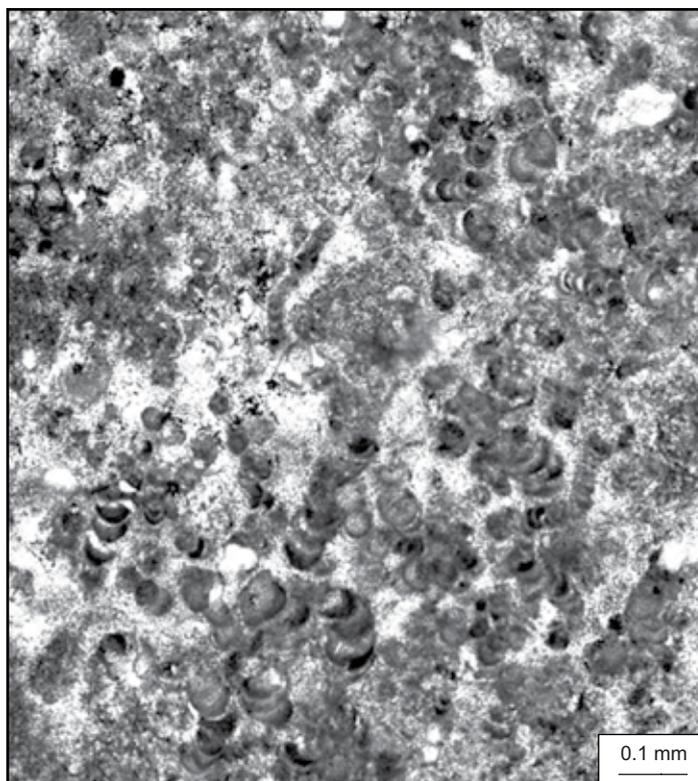


Figure 5: Calcimicrobes from microhermal nodules as illustrated by Fischer et al. (2007, their Figure 4B; reprinted by permission of Facies). They closely resemble the linear chambered microtubules here described from the Arab-A carbonate.

PALAEOENVIRONMENT

The lower part of the Arab-A carbonate contains foraminifera including *Redmondoides lugeoni*, *Trocholina alpina*, *Nautiloculina oolithica*, *Quinqueloculina* spp. and small *Valvulina* spp. (Figure 2). The microcoprolite *Favreina salevensis* is present in the upper part of this micropeloid and ooid-associated assemblage. The upper part of the carbonate displays dendroidal microbialite structures and is barren of microfossils, except for rare *Terebella lapilloides* and a monospecific, thin-walled ostracod biofacies. This upwards succession is interpreted to represent a single depositional sequence that commenced with initial flooding conducive for ooid and foraminiferal facies to be deposited, followed by gradual shallowing and probable hypersaline conditions dominated by laminated microbialite. The uppermost part of this latter lithofacies contains the chambered microtubules here described, and a very shallow-marine, restricted, possibly hypersaline or poorly oxygenated depositional environment, related to gradual shallowing of the sequence, is concluded. The microgranular and locally microstromatolitic fabrics within the upper part of the core are considered to result from a process of cyanobacterial extracellular carbonate supersaturation as described by Merz-Preis (2000).

Figure 4 (facing page): Plane polarised light thin-section photomicrographs of selected core plugs from the studied well in Qatif field, Saudi Arabia, from the Arab-A Member carbonates at core depth of 6,859.8 feet.

- (a) Grainstone consisting of microbialite granules (core plug #4).
- (b) Microbialite grainstone with microtubule network (core plug # 8).
- (c to g) Intertwined calcimicrobe tubules (core plug #8) Note their dark, possibly organic, periphery and “chamber” lining. The bifurcating specimen in the left central part of Figure 4f provides evidence for the “convex-forwards” orientation of growth.
- (g) Laminated microbialite forming microstromatolite (core plug #10).

Kopaska-Merkel and Schmid (1999) describe the forms as responsible for the construction of microbial bioherms, or microherms, consisting of microbial boundstones dominated by thrombolitic and stromatolitic textures. They consider that the preservation of the tubules results from unusual palaeoenvironmental conditions related to early cementation and protection from compaction of non-obligate calcimicrobes. Instead of microborings, the tubules are here interpreted to represent microtubules generated as a byproduct of microbial activity within similarly restricted cavities within a microbial thrombolite construction. The calcareous chambered microtubules were probably precipitated by the organism by non-enzymatic biomineralisation as described by Webb (2001). The absence of foraminifera suggests highly adverse environmental conditions for which cyanobacterial colonisation may indicate a salinity range of between 70 and 140 ppt (Warren, 2006, his Figure 9.9). Restricted marine, moderately high energy intertidal palaeoenvironment also supports similar forms, such as the Palaeozoic *Fasculus dactylus* (Konigshof and Glaub, 2004).

CONCLUSIONS

The upper part of the Arab-A carbonates in Qatif field, Saudi Arabia, is concluded to have been deposited in adverse, probably hypersaline, shallow-marine conditions that favoured the development of dendroidal, digitate microbial thrombolites, containing cavities that supported the growth of uniserial, crescentic-chambered, tubular and locally bifurcating microstructures of probable cyanobacterial origin. These microtubules are localised in the upper part of the inter-evaporitic Arab-A carbonates, that commenced with normal-marine salinity, elevated energy, shallow-marine lagoon conditions with ooids that progressively shallowed and became hypersaline or oxygen deficient in the uppermost part.

Distinction between a non-enzymatic biomineralised microtubular and microboring origin is an issue that is difficult to determine confidently with the limited evidence available. Microborings, of colonial coccoid cyanobacterial origin resemble the Recent cyanobacterial forms *Matteia conchicola* and *Solentia* sp. as well as morphological similarity to *Hyella caespitosa*. The interpreted origin of the chambered microtubules here described from intra-dendroidal thrombolitic cavities within Arab-D carbonate is considered to be more acceptable than microboring, despite some micromorphological similarities.

The microtubule-forming cyanobacteria seemed to have flourished colonially within restrictive marine conditions that excluded all shell-bearing forms except for a monospecific assemblage of thin-walled ostracods. The micropeloidal mud-lean packstones and grainstones surrounding the microborings are associated with stratiform microbialites and are evident as stromatolites within the core. The presence of a dark, microcrystalline layer to the microtubules compares well with constructed microtubules as described by Fisher et al. (2007) from the Smackover Formation, where they are compared to *Renalcis* but here considered to best resemble *Gahkumella* sp.

Although of much localised extent, the microtubules remained empty and are of interest as potential sources of intraparticle porosity in the uppermost part of the Arab-A hydrocarbon reservoir. Previously described only from the Oxfordian carbonates of Alabama, United States and Mexico, their stratigraphic and palaeogeographic ranges are now extended to the late Kimmeridgian to possibly Tithonian of Saudi Arabia.

Following submission of this paper to GeoArabia, identical forms were discovered within Arab-C carbonates in the subsurface Abu Safah Field of offshore Saudi Arabia; their relationship to the microfaunal succession is under investigation.

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5 is taken from Fischer et al. (2007) and is included with the permission of Springer. The author thanks Nestor A. Buhay II of GeoArabia for designing the final graphics.

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