Neoproterozoic microbialites in outcrops of the Qarn Alam salt dome, central Oman

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ABSTRACT

Limestones and mixed limestone and dolomite facies from the Neoproterozoic to early Cambrian Ara Group are exposed as blocks and rafts by the surface-piercing Qarn Alam salt dome in central Oman. These limestones and dolomites compose laminite-stromatolite-thrombolite-evaporite shallowing-up successions, and are remarkable in that they contain well-preserved microbial textures and fossils (both calcite and dolomite with very small but significant silicates and other mineral species) as well as pristine syn-depositional to very early diagenetic cements from the first stages of sediment lithification.

The facies are described at scales ranging from outcrop (1–100 m) to the SEM (μm-scale). Outcrop-scale sedimentology and high-resolution stratigraphy are described in detail, and petrographic and geochemical analyses are recorded. The depositional environment is interpreted to have been shallow marine subtidal to intertidal and hypersaline supratidal, with low-energy tidal flats and channels, lagoons or salinas, and continental sabkhas.

Both calcitic and dolomitic phases show microbial fossils and structures with fabrics of mineralised extra-cellular polymeric substances (EPS). The occurrence of syn-sedimentary primary dolomitic matrix in thrombolites is interpreted to result from the degradation of a thicker microbial mat, during or after growth, which provided the right micro-environmental conditions for the precipitation of dolomite. A caliche crust and sabkha evaporites (the white band) cap the laminite-thrombolite succession and together with karst breccias, fracture fills and neptunian dykes, record an emersion at the top of each of the depositional units.

Stable isotopes of carbon and oxygen of the microbialite to evaporite facies show close values for δ¹³C (+2‰ to +4‰) but a broader range of δ¹⁸O (+0.5‰ to -5‰). These values, and their spread recorded within sets of laminae, indicate little to no diagenetic resetting and therefore should be close to original equilibrium values for seawater and early diagenetic fluids. Later diagenetic cements in fractures show entirely different values with δ¹³C in the range of -2‰ to -6‰, and δ¹⁸O from -7.5‰ to -11‰.

 Whereas dolomite shows no post-depositional diagenetic modification and records preservation of finely detailed EPS mineralisation, the calcite of clumps of clots and mesoclots shows neomorphism with reorganisation into crudely fascicular-optic crystals that cut across primary sediment and early diagenetic cement fabrics.

Preservation of both sedimentary facies and the fossil record is remarkable for these ca. 540 million year old rocks and indicates that diagénesis had little effect on the microbialites at Qarn Alam.

INTRODUCTION

The Geological Context

Qarn Alam (Figures 1 and 2) is one of six surface-piercing salt domes in central Oman (Peters et al., 2003; Reuning et al., 2009). These “domes” are visually striking, rugged and irregular morphological features that break the monotonous flat desert landscape, and are halokinetic extrusions rising from...
Figure 1: (a) Simplified tectonic map showing the distribution of the Neoproterozoic to early Cambrian salt basins in Interior Oman and the location of the salt domes from Peters et al. (2003). The map shows the location of the six surface-piercing salt domes in interior North Oman and the distribution of the main tectono-stratigraphic units. Qarn Alam is highlighted in blue. (b) Qarn Alam surface-piercing salt diapir and Ghaba dome (buried) illustrating the deep-rooted nature of these salt structures, from Peters et al. (2003).
Figure 2: (a) The Qarn Alam outcrops seen from the northeast. Blocks 4, 6 and 27 are referred to in the text. The field of view is about 500 m wide. (b) Geological map of the Qarn Alam salt dome outcrops, from Al Balushi (2005). Four lithological groups are distinguished: gypsiferous conglomerates; carbonate breccias; thrombolitic carbonates; Ara carbonate facies; finely laminated carbonates. Quaternary deposits surrounding the blocks and rafts are grouped together under “sand and gravel”.

SG Sand and gravel
Late Ediacaran (Birba Formation)
GC Gypsiferous conglomerates
CB Carbonate breccias
TC Thrombolitic carbonates
ACF Ara carbonate facies
FLC Finely laminated carbonates
- - Fault
- - Bedding strata
- - Horizontal strata
- - Vertical strata
(or at least linked to) the Ara Group evaporites (Gorin et al., 1982; Amthor et al., 2003; Schröder et al., 2003). The 10 km deep Ghaba Salt Basin is one of the three major Neoproterozoic–Cambrian salt basins of Interior Oman, together with the Fahud Salt Basin to the northwest and the South Oman Salt Basin (SOSB) further south. Peters et al. (2003) give a concise but well-documented account of the geology and the history of research on the Ghaba Basin salt domes, the successive studies of which have been intimately linked to petroleum exploration.

Each of the surface-piercing diapirs brings up blocks and larger rafts of a variety of more-or-less deformed Proterozoic to lower Cambrian facies, among which the most common and widely distributed are the “dark, organic-rich, finely laminated carbonates” first reported by Dunham (1955). Subsequently, Nicol and Magnee (1964) “inferred that the laminated carbonates had been deposited in tidal-flat settings where they would have been susceptible to early dolomitization”. According to Kent (1979): “The larger rafts and blocks (tens to hundreds of metres in size) generally display successions of several of these rock types, and commonly contain a cyclic arrangement of facies, suggestive of primary deposition within a predominantly carbonate-evaporite environment”. All three quotes are cited from Peters et al. (2003). The carbonates and evaporites that crop out at Qarn Alam belong to the Ediacaran–early Cambrian Ara Group (Peters et al., 2003; Al-Siyabi, 2005; Al Balushi, 2005; Reuning et al., 2009). The microbial origin of the Ghaba salt domes carbonates has generally been accepted (Peters et al., 2003; Al-Siyabi, 2005), in spite of the lack of any direct evidence other than the general facies types.

One recent innovation regarding the sedimentology of the Ara Group, both in the subsurface (SOSB) and on outcrop (e.g. Qarn Alam), was to interpret the laminates to be deeper-water deposits rather than shallow-water to intertidal facies as previously thought. Most laminate and crinkly laminate facies (particularly laminates with high TOC content) are interpreted to be deeper-water, down-slope to basin sediments based on thicker facies sequences from turbidites to laminates and then to thrombolites (Pope et al., 2000; Peters et al., 2003; Schröder et al., 2003, 2005; Al-Siyabi, 2005). This re-interpretation is built on outcrop observations made on late Proterozoic Nama Group carbonates in Namibia (Saylor et al., 1995; DiBenedetto and Grotzinger, 2005) and from observations on stringer cores from the SOSB. Indeed the Namibian Ediacaran reefal carbonates (Omkyk member) and shoreface grainstones to offshore platform laminates (Hoogland member) of the Kuabis subgroup in the Zebra River area have served as the major outcrop analogue for the SOSB Ara carbonates for many years (Adams et al., 2004, 2005).

**The Aim**

Microbial carbonates stand out recently as a distinctive topic in sedimentology and stratigraphy, both as a focus in academic research and as a particular carbonate reservoir type in the industrial search for oil and gas. The interpretation of carbonate growth and deposition as a direct consequence of microbial activity has generally been more readily accepted for Proterozoic carbonates (given the absence of other carbonate producing life forms) than for Phanerozoic deposits, but not always with diagnostic evidence of the pathway from microbe to carbonate (Grotzinger and Knoll, 1999).

Dolomite has recently been shown to form as a microbially mediated primary sediment (Vasconcelos et al., 1995; Vasconcelos and McKenzie, 1997) after longstanding, unsuccessful attempts to form this mineral under simple, earth-surface conditions (Land, 1998; Burns et al., 2000). Microbialites in general and microbial calcite and dolomite in particular have recently become topical in exploration and production worldwide. In addition to the Smackover of the Gulf of Mexico (Mancini et al., 2000), and to the Proterozoic “Stringers” of Oman (Al-Siyabi, 2005), the identification of microbial facies (and plausible fossilised EPS) as a major component of the PreCaspian Tengiz giant field (Collins et al., 2006; Andres et al., 2012), and the discoveries of Pre-salt microbialite reservoirs in giant fields of the Santos Basin offshore Brazil (Carminatti et al., 2008), have sparked a renewed funding of research on microbialites and the study of their outcrop analogues (Harris et al., 2013).
The microbialites of Qarn Alam therefore have a place in two topical conversations: (1) microbial versus chemical primary deposition, and (2) possible modification of primary fabrics during later diagenesis. Regarding the microbialites: what is the evidence that these rocks are the direct product of microbial activity? And then the dolomites: are they a primary feature related to a microbial origin of the dolomite (Vasconcelos et al., 1995; McKenzie and Vasconcelos, 2009; Bontognali et al., 2010) or are they perhaps a secondary product from diagenetic modification (Reuning et al., 2009)?

This study builds on (and integrates) the work carried out by Said Al Balushi for his MSc project at the JVRCC Carbonate Research Centre of Sultan Qaboos University (Al Balushi, 2005), with further detailed sedimentological analyses on the Qarn Alam outcrops, and petrographic and geochemical analyses made in the Petrobras Research Centre (CENPES) in Rio de Janeiro.

The study synthesizes data at scales of observation from 100 m to 1 μm, using various geological, sedimentological, stratigraphic, petrographic and geochemical “toolkits” in order to possibly identify microbial fossils or mineralised EPS (both in calcite and dolomite), and to understand the occurrence and nature of the dolomite.

The study aims are (1): to identify and interpret the various different facies, their depositional environments and the nature of the stratigraphic genetic units; and (2) to document the microbial origin of the rocks, and to differentiate and clarify the primary depositional and very early diagenetic (syn-depositional) mineral phases and events from any later diagenetic modifications of texture, form and chemistry.

**METHODOLOGY**

**Fieldwork**

Fieldwork comprised geological mapping at the scale of 1:1,000; facies sedimentology (facies at 1 mm–1 m scale and geometries at 1–10 m scale); section measuring with cm-scale precision; and sampling for petrographic and geochemical laboratory analyses.

An initial phase of fieldwork comprised reconnaissance of the outcrop area and inventory of the mappable lithological groups. Mapping was then carried out with the geology drawn on aerial photographs. The field minutes were transposed onto a detailed topographic base map, supplied by the Geomatics Department in Petroleum Development Oman (PDO).

Observations of stratigraphic and sedimentological features were made on all blocks and rafts (1–100 m size) at the Qarn Alam outcrop (Figure 2). Facies, facies transitions and facies associations were recorded and stratigraphic cycles were identified as well as their stacking patterns. Sections were measured on the two largest blocks of laminite-stromatolite-thrombolite-evaporite facies (blocks 4 and 6, Figure 3), recording both the stratigraphic and sedimentological detail and the sample locations.

The outcrops were visited numerous times both prior to and following the mapping (between 2003 and 2013) and additional details were observed at the outcrop scale, particularly on slabbed samples, during the petrographic and analytical studies. This iteration between scales of observation allowed by successive visits was of significant value in linking microscopic detail of laboratory analyses (optical, petrographic and geochemical) with the macroscopic observations in the field.

**Laboratory Work and Procedures**

Laboratory studies comprised visual and binocular microscope observation on slabbed and polished samples; optical microscope analysis of large size 6 x 10 cm thin-sections of slabbed samples impregnated with blue resin; optical microscope analysis of 2.5 x 3.5 cm sized thin-
sections, both with and lacking blue resin. Thin-sections of the samples that were studied under the light microscope were stained with alizarin-red and potassium ferricyanide (slightly modified after Dickson, 1966).

The mineralogical composition of the sediments was determined and/or confirmed by X-ray diffraction techniques. Bulk sediment was powdered with a McCrone mill and analysed by XRD with a RIGAKU D/MAX-2200/PC diffractometer, using K-alpha radiation of copper under 40 kV and 40 mA.

For the analysis of clay minerals, samples were ground and treated for 30 minutes in 2N HCl to eliminate carbonates, then rinsed and centrifuged to remove the acid and to normalise the pH. The samples were immersed in distilled water and further separated by ultrasound probe for about 3 minutes. Material contained in smaller than 2 μm size fraction (in stable suspension) was concentrated by centrifugation and the resulting slurry was prepared on smear slides. The slides were treated with ethylene glycol and heated to 490°C in order to identify clay minerals. Clay mineral preparations were analysed by XRD with a RIGAKU D/MAX-2200/PC diffractometer, using copper K-alpha radiation under 40 kV and 40 mA with filament windows of 2 mm, 0.3 mm and 0.6 mm. The sweep speed of the goniometer was 6 degrees per minute.

Cathodoluminescence analyses were performed using a CL8200 MK5 system by CITL with a Zeiss model A1 microscope, 11 kV energy and 228 μA current, vacuum of 0.105 mbar.

For organic matter detection, thin-sections were analysed with fluorescence, using a light microscope with a blue filter and a mercury lamp HBO 100 as a source. For TOC analyses, rock samples were powdered and sieved to collect the 80-mesh particle size fraction. Samples previously acidified with hydrochloric acid (HCl) to remove the carbonate mineral fraction were analysed with a LECO SC-144 and infrared detector. The residue of sample aliquot not eliminated was used for analysis as well for the calculation of the insoluble residue (% RI = [weight of insoluble - PI / PA weight of sample] x 100).

Scanning electron microscopy (SEM) observations and analyses, both on polished thin-section and on freshly broken sediment fragments, were performed with a JEOL JSM6490LV (vacuum of 15 kV and working distance of ca. 10 mm). The SEM is equipped with an OXFORD INCA energy dispersive X-ray spectrometer. Samples were coated in an EMITECH K950X plasma chamber.

Oxygen and carbon-isotope analyses were performed with a KIEL IV Carbonate Device (online system) and CO₂ gas was analysed with DELTA V PLUS, Thermo Finnigan mass spectrometer. Powders from microdrilled samples were introduced in reaction bulbs and were dissolved with orthophosphoric acid at 70°C for 4 minutes. The data are expressed in the VPDB-notation. The reproducibility of the results is better than or equal to 0.02‰ for δ¹³C and better than or equal to 0.03‰ for δ¹⁸O.

**FACIES, DEPOSITIONAL PROCESSES AND ENVIRONMENTS, GENETIC UNITS AND STACKING PATTERNS**

Mapping of the blocks and rafts that compose the rocky outcrops of Qarn Alam (Figure 2b) distinguishes five easily identifiable lithological associations (Table 1) that comprise: (1) finely laminated carbonates; (2) laminite-stromatolite-thrombolite-evaporite successions (Figure 3) called Ara facies by Peters et al. (2003) and Al Balushi (2005); (3) thrombolitic carbonates; (4) more or less silicified carbonate breccias; and (5) gypsiferous conglomerates. The blocks and rafts of the five different facies types “float” in a gypsum- and anhydrite-dominated matrix (Peters et al., 2003; Al Balushi, 2005), and are scattered across the outcrop area with no clear organisation. Quaternary gravels and sands surround and separate the blocks and rafts, with type 1 lithologies occupying more of the northern area, types 2 and 3 the central to southern portions, and types 4 and 5 the southern to central parts (Figure 2b).
Figure 3: Laminate-thrombolite succession at the type section location on block 6 (Figure 2b). (a) General view. Numbers 11–18 refer to sample locations (or laterally equivalent layers). The blue pencil for scale measures 14.5 cm. (b) Schematic measured section of the laminate-stromatolite-thrombolite-evaporite succession at the type section location. Facies A to H and I (not visible from this viewpoint) are described in the text and are illustrated with separate figures. The colours distinguish the major facies types: grey for planar laminates (A), yellow for crinkly laminites (B), green for stromatolitic, layered and massive thrombolites (C, D, E), blue for digitate bushy thrombolites (F), yellow again for the caliche crust and other facies capping the thrombolites (G) and violet and brown for the evaporites, dolomites and collapse breccias of the white band (H).
| Table 1 |
|---------------------------------|
| **Facies** | **Description** | **Porosity** |
| Facies A1 | Very finely to finely, regularly laminated micrite to calc-siltite (Figure 4a, wackestone to packstone, mostly calcite, Figure 4b, 4c) | No visible porosity other than recent open-fracture porosity, either on outcrop or thin-section scale. Minor vuggy and interparticle porosity occurs along lamina interfaces and lamina-parallel stylolite seams, yet on a very fine scale (less than 5%). The vugs are elongate in shape, oriented parallel to laminae, and range in size from 0.1 to 0.5 mm. Most of the interparticle porosity is associated with the micritic laminae. On thin-section scale, the porosity is less developed in the micritic laminae. Porosity is patchily distributed, with areas of fine interparticle and vuggy porosity occurring in very fine laminae. Small vugs are present along lamina interfaces and lamina-parallel stylolite seams, yet on a very fine scale (less than 5%). The vugs are elongate in shape, oriented parallel to laminae, and range in size from 0.1 to 0.5 mm. Most of the interparticle porosity is associated with the micritic laminae. On thin-section scale, the porosity is less developed in the micritic laminae. Porosity is locally high, ranging from 10% to 30%, estimated from visual comparison charts. |
| Facies A2 | Planar laminated calcite and calcite-rich dolomite (Figure 5a) | Fine-scale interparticle and vuggy porosity is clearly visible along laminae, with vugs ranging in size from 0.1 to 0.5 mm. The interparticle porosity is associated with the micritic laminae. On thin-section scale, the porosity is less developed in the micritic laminae. Porosity is patchily distributed, with areas of fine interparticle and vuggy porosity occurring in very fine laminae. Small vugs are present along lamina interfaces and lamina-parallel stylolite seams, yet on a very fine scale (less than 5%). The vugs are elongate in shape, oriented parallel to laminae, and range in size from 0.1 to 0.5 mm. Most of the interparticle porosity is associated with the micritic laminae. On thin-section scale, the porosity is less developed in the micritic laminae. Porosity is locally high, ranging from 10% to 30%, estimated from visual comparison charts. |
| Facies B | Coarsely to irregularly laminated carbonate and calcisiltite (wackestone to packstone), with darker bands of very fine calcite and dolomite (Figure 6a, 6b) | No visible porosity other than recent open-fracture porosity, either on outcrop or thin-section scale. Minor vuggy and interparticle porosity occurs along lamina interfaces and lamina-parallel stylolite seams, yet on a very fine scale (less than 5%). The vugs are elongate in shape, oriented parallel to laminae, and range in size from 0.1 to 0.5 mm. Most of the interparticle porosity is associated with the micritic laminae. On thin-section scale, the porosity is less developed in the micritic laminae. Porosity is patchily distributed, with areas of fine interparticle and vuggy porosity occurring in very fine laminae. Small vugs are present along lamina interfaces and lamina-parallel stylolite seams, yet on a very fine scale (less than 5%). The vugs are elongate in shape, oriented parallel to laminae, and range in size from 0.1 to 0.5 mm. Most of the interparticle porosity is associated with the micritic laminae. On thin-section scale, the porosity is less developed in the micritic laminae. Porosity is locally high, ranging from 10% to 30%, estimated from visual comparison charts. |
| Facies C1 | Coarsely to irregularly laminated calcite and calc-siltite (wackestone to packstone) | Fine-scale interparticle and vuggy porosity is clearly visible along laminae, with vugs ranging in size from 0.1 to 0.5 mm. The interparticle porosity is associated with the micritic laminae. On thin-section scale, the porosity is less developed in the micritic laminae. Porosity is patchily distributed, with areas of fine interparticle and vuggy porosity occurring in very fine laminae. Small vugs are present along lamina interfaces and lamina-parallel stylolite seams, yet on a very fine scale (less than 5%). The vugs are elongate in shape, oriented parallel to laminae, and range in size from 0.1 to 0.5 mm. Most of the interparticle porosity is associated with the micritic laminae. On thin-section scale, the porosity is less developed in the micritic laminae. Porosity is locally high, ranging from 10% to 30%, estimated from visual comparison charts. |
| Facies C2 | Coarsely to irregularly laminated calcite and calc-siltite (wackestone to packstone) | Fine-scale interparticle and vuggy porosity is clearly visible along laminae, with vugs ranging in size from 0.1 to 0.5 mm. The interparticle porosity is associated with the micritic laminae. On thin-section scale, the porosity is less developed in the micritic laminae. Porosity is patchily distributed, with areas of fine interparticle and vuggy porosity occurring in very fine laminae. Small vugs are present along lamina interfaces and lamina-parallel stylolite seams, yet on a very fine scale (less than 5%). The vugs are elongate in shape, oriented parallel to laminae, and range in size from 0.1 to 0.5 mm. Most of the interparticle porosity is associated with the micritic laminae. On thin-section scale, the porosity is less developed in the micritic laminae. Porosity is locally high, ranging from 10% to 30%, estimated from visual comparison charts. |
| Facies D | Coarsely to irregularly laminated calcite and calc-siltite (wackestone to packstone) | Fine-scale interparticle and vuggy porosity is clearly visible along laminae, with vugs ranging in size from 0.1 to 0.5 mm. The interparticle porosity is associated with the micritic laminae. On thin-section scale, the porosity is less developed in the micritic laminae. Porosity is patchily distributed, with areas of fine interparticle and vuggy porosity occurring in very fine laminae. Small vugs are present along lamina interfaces and lamina-parallel stylolite seams, yet on a very fine scale (less than 5%). The vugs are elongate in shape, oriented parallel to laminae, and range in size from 0.1 to 0.5 mm. Most of the interparticle porosity is associated with the micritic laminae. On thin-section scale, the porosity is less developed in the micritic laminae. Porosity is locally high, ranging from 10% to 30%, estimated from visual comparison charts. |
| Facies | Type and Localisation | Description | Porosity |
|--------|-----------------------|-------------|----------|
| **Facies E1** (Figure 12) | | Layered thrombolite similar to Facies D, this additionally shows erosional and aggradational accretion features (Figure 12a). The fairly regular banding of the layered thrombolite (Facies D) passes upwards to a similar facies (Figure 12b, 12c) but this has clear lateral discontinuities in layering from erosional truncation forming 10 cm to metre-scale broad, shallow concave-upward geometries. Renewed growth and deposition above truncations creates "scour and growth" fabric, as opposed to the well-known scour and fill of current-generated cross bedding. | Porosity is patchily distributed, with clots and patches of clots showing little porosity and intermediate areas showing residual vuggy interparticle, open microfracture, and possibly vuggy leached porosity. Visual estimation over 10 cm² suggests 30% porosity. |
| **Facies E2** (Figure 13) | Massive thrombolite, homogeneous, clotted texture (block 6, 21°21’20.64”N, 57°11’55.34”E) | This rather featureless, spotted or speckled "leopard skin" facies is massive and homogeneous and shows neither laminar nor bedding (Figure 13a). The facies varies from 0 cm to 50 cm in thickness, and is found overlaying the higher energy scour and growth thrombolite facies, at the base of the radiating digitate thrombolite facies. The lower boundary of this facies, from the previous layered thrombolite, appears to be gradual. The upper part of this facies, also gradual over a few cm, is irregular and wavy with a 20-50 cm wavelength. The pattern of the digitate thrombolite above this surface radiates away from it at a right angle. | Porosity is patchily distributed, with low-porosity, more calcitic patches (Figure 13b), and high porosity dolomite-rich zones (Figure 13c). Brecciation and fractures are cemented by calcite (Figure 13c, 13d), whereas finer-grained dolomite rich matrix shows a visual estimate of 15%–30% fine interparticle to fine vuggy porosity. |
| **Facies F** (Figure 14) | 10 cm- to >1 m-thick beds of framestone (Figure 14a, 14b) with an irregular base but a flat top, composed of darker digitate mesoclots (calcitic) surrounded by or embedded within a lighter, coarser-grained dolomitic matrix. The cm-scale featureless mesoclots stems have smaller lateral protuberances and show a generally upward simple multiple bifurcation or branching pattern. The digitate mesoclots are oriented at right angles to the lower boundary of the bed, diverging where the bed has an upward curvature and converging where the bed has a concave geometry. With the upward growth pattern, circular cross section and lack of any remnants, the facies must have been a non-mineralised organic growth. This is clearly not a burrow or a leaching fabric, with no evidence of penetration, boring or dissolution either upward from the base or downward from the top. The mesoclots have a regular circular cross-section, and in thin-section they are seen to be composed of sparry calcite, whereas the matrix is composed of fine-grained highly porous dolomite (Figure 14d, 14e). A residual "ghost" fabric of fine layers of darker inclusions is seen to run through the mesoclots. The digitate fabric fills in scours and channels and builds up to a regionally extensive, flat surface with a caliche crust (Facies G, Figure 14c). | Porosity, locally very high, is most irregularly distributed in this facies. Calcitic mesoclots and early calcite cements lack any porosity, seen at the thin-section scale. Later fractures (partially to fully cemented) cut across both calcitic mesoclots and dolomitic matrix. The dolomite-rich matrix around and between mesoclots shows very fine, fine and medium scale interparticle to vuggy porosity. Larger inter-mesoclots vugs leave mm- to cm-scale pores, the larger vugs being too big to have been plugged by blue resin. Porosity over 10 cm² is up to 25%-40% or more from visual estimation. |
| **Facies G1, G2, G3** (Figure 15) | Capping facies on bushy thrombolite (block 6, 21°21’20.64”N, 57°11’55.34”E) | Three types of subfacies (Figure 15a) lie directly on, or fill fractures cutting down into the bushy thrombolite. Facies G1 is a 1 cm- to 10 cm-thick crust or layer of fine breccia grading upwards to micrite with a transitional contact both from the thrombolite below and to the evaporite and dolomite above (Figure 15b, 15c). Facies G2 are larger, cm-wide and 10 cm or more long fracture or dyke fills, composed either of cements (including anhydrite, Figure 15d, 15e) or of grannoid silt or sand deposits. Facies G3, absent on outcrop block 6, is a finely laminated, more coarsely and irregularly crinkly laminated dolomite that forms a bed directly on top of the uppermost cycle of the stacked cycles on outcrop block 4 (Figure 15f). | The Facies G1 microbreccia is tightly cemented with some residual vuggy pores not fully occluded by calcite cement. Such pores may be surrounded by concentrations of organic matter (bitumen). Vuggy and interparticle porosity develops where Facies G1 passes to the evaporites of Facies H. Facies G2 is also tightly cemented but with a minor amount of porosity developed along microfractures and stylolites with local channelling and dissolution. Facies G3 shows considerable fine to coarse vuggy, inter- and intra-laminate porosity of 25-40%. |
| **Facies H1, H2** (Figure 16) | Dolomites and evaporites (H1) collapse breccia (H2) (block 6, 21°21’20.64”N, 57°11’55.34”E) | The bed capping thicker sequences of laminites and thrombolites, as in block 6 (Figure 16a) and the thicker sequence of block 4 (Figure 16b), is composed of cm-thick, fine-grained pale dolomite alternating with pale to white, fine-grained gypsum and aragonite (thin-section optical microscope and XRD analyses, Al Balushi, 2005). These two individual facies pass laterally and vertically into a carbonate-cemented collapse breccia. | Vuggy and interparticle porosity is low to locally very high (Figure 16c, 16d, 16e) and is most irregularly distributed in this facies. |
| **Facies I** (Figure 17) | Finely laminated, partially silicified carbonates (block 6, 21°21’20.64”N, 57°11’55.34”E) | Very finely and regularly wavy-laminated stromatolitic carbonate (Figure 17a, 17b, 17c), with mm- to cm-high domes measuring cm to 10s of cm in width. Laminae are very regular and show up as alternating lighter and darker sub-mm to mm thick layers. Patchy chertification is common in this layer, which lies directly above the evaporites of block 6 and block 4. | The impregnated thin-section shows very limited visible porosity in open microfractures, and is also suggestive of some extremely fine porosity in certain slightly thicker laminae. This is, however, at the limit of optical resolution. |
This study focuses on the Ara facies of Qarn Alam (lithological association, Figure 3) comprising a succession of laminite-stromatolite-thrombolite-evaporite facies. There is no evidence of any primary stratigraphic relationship between the Ara facies and the other lithological associations (other than their being grouped in the same surface piercing structure), although the lithological association 1 (very fine laminites with mudstone turbidites) may represent a coeval deeper-water basinal facies equivalent to the shallower Ara facies (Al Balushi, 2005). The lithological association 1 contains fine breccias, graded beds of calcisiltite to mudstone, finely laminated mudstone and chert layers as well as silicified laminites. These finely laminated carbonates weather a pale grey to darker grey, but would not fall under the category of “dark, organic-rich, finely laminated carbonates first reported by Dunham” (Peters et al., 2003), as certainly would the Ara facies of blocks 1, 4, 6, 13, 17, 29 and 30 (Figure 2b), in spite of the general lack (when analysed) of organic matter.

The Ara facies are easily recognised at Qarn Alam even from afar by the conspicuous thin but regular white band of evaporite facies that marks the top of each shallowing-up cycle (Peters et al., 2003; Al Balushi, 2005). A reference section of the Ara laminite-stromatolite-thrombolite-evaporite facies succession (Figure 3a) was measured on the northwest face of block 6: 21°21'20.64"N, 57°11'55.34"E (Figure 3). The location was chosen for the quality of the exposure and the more numerous facies in continuity there than on the other blocks. The section measures some 7 m from base to top of the carbonate-evaporite succession (Figure 3b), and is composed of nine facies, A through I, with a number of sub-facies. The base of the section is close to the contact of the block and the surrounding gypsum-dominated matrix of the diapir in which the blocks and rafts are floating. The block shows a brecciated zone at the contact and the measured section begins above the brecciated zone, starting from where there is stratigraphic continuity of the Ara facies.

The whole measured section is in clear stratigraphic continuity with no major breaks and shows a single depositional sequence. Facies transitions are gradational to sharp, clearly indicating a shallowing-up cycle from subaqueous laminites, through thrombolites, to a caliche crust with an evaporite layer above the caliche that indicates an emersion surface. The caliche crust and evaporite layer of the Ara facies are clearly in stratigraphic and sedimentological continuity with the facies below and above, and have no genetic relation to the evaporites and gypsum of the diapir matrix. The section above the measured interval continues with crinkly laminites and layered thrombolites of one or more additional cycles but also shows some tight refolding. The measured interval is restricted to a part of the outcrop that has not been refolded.

Fieldwork provided observations on facies (the combinations of lithologies and sedimentary structures, Gressly, 1838; Cross and Homewood, 1997) as well as on facies associations and sequences and on depositional geometries. This facies sedimentology was then the basis for interpretations of depositional environments and facies models, depositional cycles or genetic units, and the stratigraphic stacking patterns of genetic units (Busch, 1959; Homewood et al., 1992, 2000).

**Facies Descriptions**

Descriptions of Facies A1 to Facies I (Figure 3a, 3b) are detailed in Table 1 and illustrated in Figures 4 to 17. Three microbialite facies have been further described in Table 2 (Facies A2, C and F) and the observations on petrography, mineralogy and geochemistry are illustrated in Figures 18 to 23.

The facies are described and interpreted from base to top of the reference section. However, Facies A1 is not in stratigraphic continuity with the Ara facies but is one of the other mapped units (Figure 2b: composing blocks 27, 28, 31, a smaller block between blocks 1 and 4, and a very small block lying against the western side of block 17). A description of Facies A1 is included on Table 1 (and is brought into the discussion) since, as mentioned above, these finely laminated carbonates have been thought to be possible deeper water equivalents to the Ara facies (Al Balushi, 2005).
Figure 4: Facies A1, very fine laminite with mudstone turbidites. Location: Block 27, about 400 m away from block 6 (Figure 2b). (a) Bedding pattern with cherts and cm-thick pink coloured layer at tip of hammer handle. Hammer handle measures 40 cm. Number 10 indicates sample location. (b) Thin-section of sample 10. Right part is stained. Red colour indicates calcite composition, colourless parts are silica. (c) Photomicrograph under fluorescence mode showing clotted fabric. (d) Plane polarised light: mm-scale laminae of very fine grainy calcitic layers (dark) between grainy laminae of calcite clots (partially silicified). No organic matter.
Figure 5: Facies A2, planar laminites with mudstone beds, block 6 (Figure 2b). (a) Bedding and alternation of the laminite and mudstone lithologies, tape reel and extended tape together measure 25 cm. (b) Detail of regular planar laminite and mudstone bed, visible part of pocketknife for scale measures 10 cm. (c) Thin-section impregnated with blue resin to show the lack of visual porosity. (d) Stained thin-section indicates calcite composition. (e) Detail of thin-section under plane polarised light showing clotted fabric with neomorphic spar, and porosity developed along microstylolite lamina surface.
FACIES B: CRINKLY LAMINITES

Figure 6: Facies B, crinkly laminites, block 6 (Figure 2b). (a) Bedding pattern and vuggy porosity enhanced by surface weathering. (b) Irregular, lighter coloured grainy streaks and occasional, continuous mm-thick darker layers of clotted calcite. Metallic pencil tip measures 2 cm. (c) Stained thin-section indicating calcite composition of both darker, finer-grained micrite and lighter-coloured, coarser neomorphic microspar. (d) Blue resin impregnated thin-section showing finer and coarser interparticle and vuggy porosity. (e) Photomicrograph under plane-polarised light showing peloidal to clotted fabric, neomorphic microspar and porosity.
Figure 7: Transition zone from laminites to thrombolites. (a) Indication of transition between laminites and thrombolites with an interval where the two fabrics coexist; (b) detail of the transition zone from laminite to clotted fabrics, pencil measures 15 cm.
Figure 8: Facies C1, crinkly laminites with incipient clotted texture, block 6 (Figure 2b). (a) Detail of bedding and fabric, pencil measures 15 cm. Facies C1 is in the lower part of the image. Alternating pale and darker laminae and bands become successively more irregular. Domal stromatolitic structures appear in Facies C2, they have different sizes: 20 cm broad, 2–3 cm high dome (red arrow) and 1 cm high domes (black arrows). (b) Slabbed sample showing clotted fabric, layering and dispersed vugs. (c) Blue resin impregnated thin-section from 8b (view is 2.6 x 2.4 cm), showing clotted fabric, irregular layering and patchy distribution of interparticle and vuggy porosity. (d) Stained thin-section (impregnated with colourless resin) with pink stain of micrite and calcite microspar, very fine-grained unstained phase is dolomite. Thin-section taken from location shown in 8b.
Figure 9: Facies C2, crinkly laminites with incipient clotted texture and domal to columnar stromatolites, block 6 (Figure 2b). (a) Slabbed sample of columnar stromatolite built of a coarsely laminated, clotted fabric. Smaller clots clump together and progressively coalesce to compose larger mesoclots (blue arrow). The growth of the columns leaves a narrow (1 cm-wide) intercolumn depression that is filled in by clotted layers and a brown, fine-grained mineral phase (detail in 9c). The column heads are outlined in yellow, with at least two successive stages of infill of the intercolumn depression. A 0.5 cm-thick continuous layer, outlined in orange is shown in greater detail in 9b. Vuggy porosity is indicated with white arrows. (b) Detail of the laterally continuous darker layer, showing a clear tufted fabric with 0.5 cm high, 0.5 cm spaced spikes (orange arrows) trapping the fine-grained dark infill phase between them. This is a calcified “tufted mat” feature. The darker layers are built of individual clots, clumps of clots and mesoclots, and these are surrounded by a pale fine-grained dolomitic matrix with dispersed vugs (white arrows). (c) Detail of the infill between columnar stromatolite heads, showing the same composition as the stromatolite heads with clots, clumps of clots, mesoclots, matrix and vugs. (d) Stained thin-section showing calcite clots and mesoclots (pink-red), calcite fracture fills and dolomite of the fine grained matrix. Arrows show where microstylolite solution seams pass within a short distance to a cement-filled fracture. This indicates early differential breakage and compaction referred to as “crumbly fracturing” in the text and in Table 1.
Figure 10: Facies C2, crinkly laminites with incipient clotted texture and domal to columnar stromatolites, block 6 (Figure 2b). (a) Polished slab of stromatolite column and intercolumn depression and infill. (b–d) Three large-size blue resin impregnated thin-sections of the upper, central and lower parts respectively of the same slab. Thickness variations of laminae (Th1 = thinner laminae, Th2 = thicker laminae), clotted fabrics (e.g. yellow arrows), porosity distribution (e.g. white arrows), and cemented and unfilled fractures (e.g. orange arrow) may be distinguished. The finely crystalline dolomitic matrix is highly porous and therefore tends to acquire a blue tinge from the resin. (e) Detail of the infill between two stromatolitic columns. The left and right images show the same view, without and with overlay and comments. Fine-grained brownish material (black arrow) forming an infill between the stromatolites heads.
Figure 11: Facies D, thrombolite with layered mesoclots to domal form (e.g. yellow arrows on (a)), block 6 (Figure 2b). (a) Bands of clots and mesoclots (darker phase) alternate with pale, very fine grained matrix. The layering of bands and laminae shows a clear “double cyclicity” with bundles of thicker dark bands alternating with bundles of thinner laminae. Pencil scale is 15 cm. (b) Stained thin-section showing calcitic composition of clots and mesoclots (the darker bands on outcrop are found to be made of clear spar (e.g. blue arrows) in thin-section). (c) Thin-section under plane polarised light. Mesoclots are made of neomorphic spar with ghosts of clots and peloids (e.g. yellow arrow). (d) Stained thin-section showing calcite composition (pink colour, e.g. yellow arrow) of neomorphic spar.
Figure 12: Facies E1, thrombolite with scour and growth features, block 6 (Figure 2b). (a) 5 cm to 15 cm deep and 1 m-wide or more scour features detailed in yellow boxes (scours: yellow arrows; drapes: white arrows) are overlain conformably by renewed aggradation of banded layering (upper part of outcrop photograph, pencil is 15 cm long). These are scour and growth features (with microbial as opposed to simple mechanical draping of erosion surfaces). (b) Stained thin-section (impregnated with colourless resin), showing pink-stained calcite (mesoclots) and unstained dolomite (matrix). (c) Thin-section impregnated with blue resin. Peloidal to clotted fabric is seen within neomorphic spar of mesoclots.
Figure 13: Facies E2, massive thrombolite, homogeneous clotted texture, block 6 (Figure 2b). (a) The lower part of the photograph shows the massive and homogeneous clotted texture (labelled M) with dark mesoclots in a pale matrix. Marker pen is 12 cm long. The upper part of the photograph shows the bushy thrombolite (labelled BT) and the overlying caliche crust (labelled C). (b) Stained thin-section showing pink-stained calcite of mesoclots and fracture cements, contrasting with unstained finely crystalline matrix dolomite (labelled d). Dark material is bitumen. (c) Thin-section impregnated with blue resin; highly micro-porous dolomite matrix has a blue tinge from the resin. Numerous cemented fractures (e.g. yellow arrow) are seen. (d) Detail of thin-section under plane polarised light. Left side of image shows blocky neomorphic spar (labelled CF) and clumps of microdolospar matrix (labelled d). Upper right corner shows peloidal to clotted ghost fabric in neomorphic spar of mesoclots (labelled mc). Lower right shows bands of microdolospar matrix (labelled d1).
Figure 14: Facies F, digitate radiating or “bushy” thrombolite, block 6 (Figure 2b). (a) Abrupt transition from massive thrombolite (Facies E2) to digitate thrombolite forming a convex, 60 cm broad bushy feature (lower hat brim is 38 cm long). (b) Detail of bushy feature in 14a, showing dominant upward branching (e.g. yellow arrows) of dark digitate mesoclots in pale matrix.

See next page for continuation.
Figure 14 (continued): (c) Slabbed sample from the top of the bushy feature showing 0.5–1 cm size, circular to elongated cross section of digitate branches (labelled mc) in pale matrix (labelled d). Top of the sample shows caliche crust (labelled Cal). (d) Stained (left half) and blue resin impregnated thin-section. Highly porous microdolospar shows a blue colour from resin (labelled d). Mesoclots (labelled mc, circular cross section) and fracture cements (yellow arrow) show a pink colour corresponding to calcite, matrix is unstained dolomite. XRD analyses confirm mineralogies. (e) Detail of mesoclots cross section showing strands of microdolospar, ghost fabrics in neomorphic spar and also ghosts of clear, fine needle-shaped forms (blue circle and arrows).
Figure 15: Facies G, capping facies on bushy thrombolite, block 6 (Figure 2b). (a) Panoramic photograph showing the white band (labelled wb) above the bushy thrombolite. Karst fractures and neptunian dykes in the bushy thrombolite, up to 30 cm deep, are filled in by evaporites. (b) Caliche crust (labelled Cal, yellow arrow), evaporites and thin-bedded dolomite above the bushy thrombolite. Marker pen is 12 cm long. (c) Brecciation (labelled Br) at the top of the bushy thrombolite and progressive transition to the caliche crust. (d) Karst fracture or neptunian dyke in bushy thrombolite (Unit B of block 4). Steel chisel is 20 cm long. (e) Anhydrite, detail of thin-section from infill of Neptunian dyke in the thrombolites (15a, 15d). (f) Field sketch of karst fracture or neptunian dyke in layered thrombolite facies on unit D block 4. These fractures and dykes indicate early lithification between successive depositional cycles.
Figure 16: Facies H, dolomites, evaporites and collapse breccia, block 6 (Figure 2b). (a) Thinly bedded dolomites (labelled D) overlain by a breccia of dolomitic clasts (labelled B) in an evaporite matrix (gypsum, anhydrite). (b) Breccia of dolomite and chert clasts at the top of the “white band” (block 4). (c) Slabbed sample of pale weathering, flat bedded dolomitic stromatolite layer in white band. (d) Enlargement and detail of 16c. (e) Thin-section impregnated with blue resin shows irregular laminae and interparticle to vuggy porosity (16c).
Figure 17: Facies I, Finely laminated partially silicified stromatolite overlying the white band block 6 (Figure 2b). (a) Very finely laminated and silicified stromatolites (S) above the white band, overlain conformably by layered thrombolites of a younger cycle on block 4. (b) Detail of the same bed as 17a, note that the silicified stromatolite here is at the base of the bed. (c) Stained thin-section (staining of right half) with fine wavy stromatolitic laminations. Silicification has replaced much of the carbonate (some residual calcite is coloured pink). Residual carbonate in the lower half of the thin-section.
| Facies   | Type and Localisation                                                                 | Primary Syndepositional and Early Diagenetic Microbially Mediated Carbonate Phases |
|---------|----------------------------------------------------------------------------------------|----------------------------------------------------------------------------------|
| A2      | Planar laminites with mudstone beds (block 6, 21°21'20.64"N, 57°11'55.34"E)            | These deposits are essentially calcitic but with minor proportions of aragonite and traces of clay minerals (Figure 18f), phosphate and iron oxide. Microbial fossil forms and bacteriomorphs comprise rod shaped fossils (Figure 18a), calcite overgrowth on mineralised EPS template (Figure 18b) "horseshoe shaped" fragments (Figure 18c, 18d) of calcite-mineralised coccoid mucus sheaths, as well as mineralised alveolar honeycomb structure (Figure 18e). Observation of thin-sections under fluorescence microscopy (Figure 19a) shows preserved organic matter (Figure 19b). This is laminated, amorphous, granular matter (Figure 19c, 19d, 19e) concentrated in layers on laminae surfaces (Pacton et al., 2011). Possible acrithac (Figure 19g, 19h). |
| C, D and E | Crinkly laminites, incipient clotted texture and domal to columnar stromatolites, layered and massive thrombolite (block 6, 21°21'20.64"N, 57°11'55.34"E) | This mixed lithology is predominantly calcite and dolomite, with layered clots and clumps of clots forming 1 cm tall convex bumps to taller and broader stromatolitic heads (Figure 9 to 12). There are polyphased assemblages of alternating laminae comprising clotted growth, microcrystalline matrix, and detrital infill (Figure 20c, 20d, 20e), together with minor amounts of clay minerals, and fluorite. These successive mineral phases are repeated over and over again during sedimentation, between phases of erosion (Figures 10 and 20a, 20b). These fabrics clearly show that sedimentation encompassed times of adhesive growth (trapping and binding), of mineralised growth (clots and clumps of clots, Figure 21), of formation of microcrystalline dolomite, of erosion by currents (scouring between stromatolitic heads) and of entrapment of reworked, very fine-grained material. Microbial fossils in these thrombolites are dominated by the telltale dolomitic alveolar structures of mineralised EPS template (Figure 20f; Bontognali, 2008). Bioneralisation comprised microcrystalline dolomite and clay minerals (commonly palygorskite). |
| F       | Digitate radiating thrombolite or bushy thrombolite (block 6, 21°21'20.64"N, 57°11'55.34"E) | This is also a mixed lithology, built by a framework of digitate, arborescent, dark non-porous calcite mesoclots, which are surrounded by a pale highly porous and very finely crystalline to microcrystalline dolomite, with vuggy cavities ranging up to cm sizes (Figures 14 and 22). The mesoclots have a circular cross section, are cm-sized in diameter and have cumulative lengths of up to or more than 50 cm (Figure 14c, 14d, 14e). The pale matrix appears to a syn-sedimentary deposit, with no traces of later draping or infilling between and around an earlier growth and framework. The syndepositional nature of the matrix indicates that this is a framestone rather than a bafflestone that would have a later matrix infill. Calcite cemented fractures cut indiscriminately through both the mesoclots and the matrix, which indicates that the mesoclot framework and surrounding microcrystalline dolomite matrix were lithified and bound together before this breakage and cementation. The fractures together with the vuggy cavities are partially or totally occluded by later diagenetic calcite cements. The pale matrix is composed of microcrystalline, highly porous dolomite (Figure 22c) that suggests a clotted fabric under both the optical microscope and cathodoluminescence. SEM images, however, show the highly porous and microcrystalline nature of the dolomite matrix compared to the non-porous and partially clotted calcite of the mesoclots (Figure 22d). Higher magnification shows in detail the growth of fibrous and more sheared clay minerals (palygorskite and other, unidentified species of mica or clay minerals) that are contemporaneous with the dolomite (Figure 23). Remarkably, the alveolar textures and mineralisation are entirely similar to the EPS templates from the modern Abu Dhabi sabkha (Fig. 20A, p. 837 in Bontognali et al., 2010; Figure 22d). The alveolar structures, which are predominantly dolomite, also involve clay minerals such as palygorskite (Figure 24). Bacteriomorphs in the matrix of these thrombolites include coccoid forms (high magnesian calcite, Figure 23a) but are also dominated by the alveolar structures of dolomitic EPS templates (Figure 22d) that are mineralised by microcrystalline dolomite and clay minerals. |
Figure 18: Microbial fossils and mineralised EPS of planar laminites. (a) Rod shaped bacteriomorph fossils (indicated with a yellow arrows). (b) Calcite overgrowth on mineralised EPS template. (c) Grainy fabric (labelled c) with small “horseshoe shape” fragments of broken calcified mucus sheath (inside yellow circle). (d) Enlargement of “horseshoe shape” fragments (red arrow) of broken calcified mucus sheath (Kazmierczak et al., 2011). (e) Clay mineral fibers and microcrystalline calcite showing an alveolar honeycomb texture. (f) Glauconite platelets (labelled G).
Figure 19: Organic matter and fossils in planar laminites. (a) Organic matter concentrated on lamina surface seen under fluorescence microscope. (b) Amorphous granular organic matter under fluorescence mode. (c) Unstructured organic matter under transmitted white light. (d) Amorphous granular organic matter under fluorescence mode. (e–f) Putative acritarchs under transmitted white light.
Figure 20: Grains, cements and mineralised EPS in stromatolitic, layered and massive thrombolites. (a) 9 x 11 mm blue resin impregnated thin-section of stromatolitic thrombolite (Facies C2) with erosional scour between columnar stromatolite heads with infill laminae. See also Figure 9a, 10a, 10c, 10e. (b) SEM composed image of the yellow rectangle of 20a, lighter grey is mainly composed of calcite, darker grey is dolomite and very dark grey or black corresponds to porosity. (c) Grainy detritus of both calcite (C) and dolomite (D) in infill laminae. (d) Detail of detrital material, EDS spectrum 1 and 2 indicate quartz. (e) Well-formed dolomite crystals, overgrowth on detrital infill. (f) Alveolar structure of mineralised EPS (white arrows) with dolomite and clay minerals (yellow arrow) in massive thrombolite.
Figure 21: Microdrill sampling and SEM-EDS of stromatolitic thrombolites. (a) Sample locations on 6 x 10 cm blue resin impregnated thin-section and microdrill powder samples for stable isotope analyses. Enlargements show clotted fabrics with clots and clumps of clots, and interclot microcrystalline dolomite. (b) SEM image with locations of spot EDS analyses (Spectrum 1, 2, 3). Target area for each spectrum is about 3–5 µm in diameter. Dolomite shows very high microporosity whereas calcite is not porous. Spectrum 1 indicates (Ca, Mg) corresponding to poorly formed dolomite (not stoichiometric). Spectrum 2 and 3 indicating (Ca) corresponding to calcite.
Figure 22: Fossilised EPS in bushy thrombolite. (a) Slabbed sample of bushy thrombolite showing circular cross sections of dark mesoclots and pale surrounding matrix. (b) 2 x 3.5 cm stained and blue resin impregnated thin-section of bushy thrombolite showing blue tinge of dolomite from very high microporosity, calcite of mesoclots, streaks of microcrystalline dolomite in the neomorphic spar of mesoclots, fracture cements and empty vugs. (c) General SEM image of the contact between a mesoclots and the matrix. (d to f) Successive enlargements as labelled. (d) Mineralised EPS, alveolar structure (e.g. yellow circle) with typical 120° angles (EDS indicate Ca and Mg) and fibrous clay minerals (e.g. yellow arrow, see also Figure 23). (e and f) Enlargements of the contact between calcite (labelled Ca) and dolomite (labelled Do) showing the microporosity of the dolomite and development of neomorphic calcite crystals.
Figure 23: Bacteriomorph fossils, mineralised EPS and clay minerals of the bushy thrombolites. (a) Coccoid and coccoid chain, high magnesian calcite. (b) EPS alveolar structure (yellow arrow), mineralised by dolomite and clay minerals. (c) Dolomitic alveolar structure with some phosphate. (d) Alveolar EPS structure mineralised by Mg-Al clay minerals and dolomite. (e) Palygorskite and dolomite forming an alveolar structure. (f) Palygorskite (or other Mg-clay fibers), with a highly magnesian calcite crystal. (g) Micas, fluorite and dolomite surrounded by palygorskite fibers. (h) Palygorskite fibers. Mineralogies have been confirmed with XRD analyses.
Figure 24: Depositional geometries of the white band and bushy thrombolites. (a) Blocks 4 and 6 with the white band indicated by white arrows. The band of evaporites and thin-bedded dolomite (Facies G, H) is laterally extensive, regular and planar. (b) Closer view of the white band on block 4 (white arrow). The beds have a vertical dip with stratigraphic younging to the right. To the left of the person standing on the white band, a channel scour is visible (yellow arrow) below the bushy thrombolite (Facies G). A shear plane cuts the section at a low angle near the extreme left side of the photograph (red arrow). (c) Block 6; irregular stratigraphic contact (picked out in yellow) between bushy thrombolites (BT, Facies F) and the massive thrombolite (MT, Facies E2) and smooth contact between the bushy thrombolite and the capping beds above (Facies G, H). (d) Block 6; smooth but irregular undulatory contact (picked out in yellow) between the bushy thrombolites (BT, Facies F) and the massive thrombolite (MT, Facies E2).
Depositional Geometries

The white band of evaporites capping the laminitе-stromatolite-thrombolite facies successions (Figures 15a, 16, 24a and 24b; “sequence boundary” of Peters et al., 2003) is a major regular and continuous planar geometrical feature. These exposure surfaces (each successive cycle within a stratigraphic stack terminates with a similar white band) were clearly very flat and extensive over hundreds of metres at least. The white bands furnish an important tie to bathymetry for the Ara facies cycles since they record emersion, and the geometry shows that the upper parts of the cycles (the bushy thrombolites in particular) fill in any previous irregularities on the sediment surface, building up to a smooth and regular level ground.

In contrast to the regularity of the white band, the bushy thrombolites show considerable variations in thickness, ranging from several metres to less than a metre. The thinning of the bushy thrombolites is compensated in some places by thicker massive thrombolites, with a lateral facies substitution or an erosional scour between the two facies (Figures 24c, 24d and 25). In other locations there is a clear channel scour into the facies below the bushy thrombolites (Figure 25). Block 4 shows a 50–60 cm deep by several metres wide channel. The channel scour cuts into layered thrombolites. The scour surface is draped first by layered thrombolite and then the channel form is filled in by growth of bushy thrombolite with a white band cap of evaporites. On block 6 a deeper channel feature (2–4 m deep) cuts into the thrombolites of the measured section about 15–20 m away from the section, and is exposed at the northern tip of the raft (Figure 26). Previous authors (Peters et al., 2003; Al Balushi, 2005) have referred to this structure as a mound, but close examination shows the feature to be a channel with downward scour and with the bushy thrombolite infill building up to the laterally extensive, regular white band (Figure 26c).

Interpretation of Facies in Terms of Depositional Processes and Environment

The interpretations of Facies A to Facies I (Figures 3a and 3b) are provided in detail in Table 3. Although whether the planar laminites were deposited in deeper-water or shallow-water environments is less clear, the white band of evaporites near the top of the section is clearly linked to emersion and to a supratidal sabkha-like environment. Diagnostic features include: the caliche crust (Facies G1); small karst fractures, neptunian dikes and infill (Facies G2); microbreccias, gypsum-anhydrite-dolomite layers and collapse breccias (Facies G, H).

The measured section therefore clearly records a shallowing-up cycle that terminates with emersion and exposure with subsequent transgression. The planar laminites and mudstone beds at the base of the section, some 7 m below, may be interpreted in two ways. First as the deeper-water transition from a turbidite basinal facies to the shoreface laminitе-stromatolite-thrombolite succession, a hypothesis that could link Facies A1 to the Ara facies. A second interpretation would be that of a shallow subtidal deposit in a low-energy littoral to lagoonal environment. The deeper-water interpretation would necessitate a considerable decrease in bathymetry due to sea-level fall during the deposition of the cycle in order to produce such a thin succession (see Discussion Section below).

Depositional Environments and Facies Models

Two somewhat different depositional scenarios come from the facies succession, the depositional geometries, and the interpretations of process. The first scenario (Al Balushi, 2005) is based on the observations at Qarn Alam and the comparison of these with the facies and stratigraphic models developed for the Ara stringers in the SOSB (Al-Siyabi, 2005). In this view (Figure 27a), the laminites and mudstones at the base of the cycle described (A2) are taken to be deeper water sediments, intermediate between the shallow facies and the deep-water very fine laminites and turbidites (A1). The shallowing succession would then record the simple progradation of a depositional profile from sabkha to deeper basin, with the bushy thrombolites as a high-energy littoral facies between the sabbkas and the deepening slope with layered thrombolites and laminites, reaching basinward to turbiditic mudstones. The relatively thin succession (only 7 m for a shoreline to basin record) could be explained by a major fall in sea level during progradation,
Figure 25: Channel scour and fill, block 4. A smooth scour is overlain by massive to bedded thrombolite. A second smooth and conformable surface, 20 cm above the scour, is overlain by massive thrombolite with progressive development of the bushy thrombolite. The bushy thrombolite develops at right angles to the surfaces below, growing into the channel space, and building up to the regular planar surface of the white band. (a) Panoramic photograph from above, showing a 0.5 m deep channel scour and infill on block 4. Camera case for scale is 10 x 8 cm. (b) Sideways view of the channel on block 4 (view rotated since the dip is vertical). (c) Field sketch of the facies and geometrical relationships of the channel of Unit B on block 4.
Figure 26: Thrombolite filled channel on block 6. From south to north, the white band extends laterally as a regular planar feature (white arrows) up to where the rock face is undergoing present-day collapse and rock fall. At the northern end of block 6, the section is warped down partly by structural deformation and partly by collapse and rock fall. The base of the thrombolite facies (Facies D, E, F) is picked out with yellow arrows and shows an incision cutting down about 3 m. (a) General view of block 6 channel feature. (b) Closer view of the thrombolite filled channel on block 6. (c) Field sketch of block 6 outcrop between the “type section” location and the channel feature.
Figure 27: Depositional scenarios or Facies Models for the laminite-stromatolite-thrombolite-evaporite Ara facies at Qarn Alam. (a) High-energy steeper depositional profile system with thrombolites forming as a littoral barrier between deeper water environments (laminites) and playa and sabkhas areas (evaporites). This model is based on the type section at Qarn Alam as well as on analogies with Ara carbonates from the SOSB and Nama Group late Proterozoic analogs in Namibia. (b) An alternative model is based only on the sections at Qarn Alam. A low-energy and very low-angle depositional profile system with extensive tidal flats (layered thrombolites, stromatolites, and crinkly laminites) between a shallow subtidal environment (planar laminites) and an extensive lagoonal or salina zone (bushy thrombolites) on the sabkha. Ebb tidal aprons or beach barriers accumulate grainy deposits to form massive thrombolites.
| Facies          | Name and Depositional Environment                                                                 | Interpretation of Facies in Terms of Depositional Processes and Environment                                                                 |
|----------------|-----------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------|
| **Facies A1**  | Very fine laminite with mudstone turbidites (block 27, 21°21'32.48"N, 57°11'54.35"E)      | Alternating mm-scale varve-like laminae may result from different physical and chemical (including biochemical) processes for each lamina, such as suspension fall-out, seasonally driven (or longer-term climate driven) chemical precipitation, or sediment gravity flow. The thicker, homogeneous micritic mudstones, with randomly varying thickness in the vertical sequence, are thought to be “dilute turbidites” deposited by sediment gravity flow. The varve-like facies indicates a very low energy environment, and together with the turbiditic mudstones the facies is diagnostic of a deep-water or basinal depositional environment. Chert is a later, diagenetic phase that cuts across primary sedimentary laminae. There is no evidence in this facies for any organic matter or any process of microbial origin such as trapping or binding of grains. |
| **Facies A2**  | Planar laminites with mudstone beds (block 6, 21°21'20.64"N, 57°11'55.34"E)                | Planar to very low amplitude undulatory silt-grade laminae may result from different physical processes for each lamina, such as suspension fall-out or sediment gravity flow, with some low intensity current action. The thicker, homogenous micritic mudstone, with randomly varying thickness in the vertical sequence, may have been deposited either by sediment gravity flow (dilute turbidites) or from suspension fallout after storms. The planar laminated facies indicates a low-energy environment, and if the mudstones were to be turbiditic, then the facies might indicate a fairly deep-water depositional environment (but certainly less deep than Facies A1) and dominated by physical as opposed to biological processes, with low-energy current activity (distal storm or contour current deposits). If the mudstones were not turbiditic in origin, then the depositional environment could have been either very shallow (lower intertidal flats) or moderately deep (distal storm deposits). These deposits contain abundant reworked fragments of microbial origin, and laminae surfaces show apparently non-reworked microbial fossils and alveolar structures (mineralised EPS, see further discussion below in the next section). This is a clear evidence of the development of a thin microbial film on successive sedimentary surfaces. Organic matter may have accumulated from in-situ growth, or from reworking, or from both. |
| **Facies B**    | Crinkly laminites with irregular grainy streaks (block 6, 21°21'20.64"N, 57°11'55.34"E)      | Although some oblique laminae may preserve ripple cross-lamination in places, the dominant crinkly fabric shows irregular accretion by agglomeration of grains (including clots and peloids) and micrite in fine layers. This suggests trapping and binding of material, and is interpreted to result from the development of microbial mats. The general lack of evidence for higher energy and stronger currents may result from stronger binding of grains during deposition, and may not be indicative of specific bathymetry, but the sediments were presumably within the photic subtidal to intertidal zone with most probable cyanobacterial development. The relationships of pores and bands of pores with microstylolite seams suggest that the porosity is at least partly “secondary”, due to leaching during very early diagenesis (see discussion on early diagenesis and the discussion section). |
| **Facies C1**   | Crinkly laminites with incipient clotted texture and domal to columnar stromatolites (block 6, 21°21'20.64"N, 57°11'55.34"E) | The various convex forms of strings of clots and mesoclots with cm to 10 cm moulded to columnar vertical accretion are composed of successive layers of coarse laminae. Although they are clotted and not coarsely laminated, they are clearly stromatolite forms. Given the gradual transition from simply laminated to clotted fabric, both Facies C1 and C2 are grouped together here. The columnar stromatolites (C2) are subtidal to intertidal microbial growth structures that had synoptic relief of several cm to 10 cm above the surrounding sediment surface. The irregular shape of clots and the varying thickness of laminae indicate biological growth as opposed to simple chemical precipitation. Some laminae or layered mesoclots show a “spiky” or tufted shape suggestive of the “tufted mat” fabrics of present day subtidal to intertidal microbial mats (Figure 9a, 9b), such as those described by Strohmenger et al. (2011). The outer layer of sparry calcite enclosing a finer core of brownish groundmass in some clots suggests that the clear sparry calcite that now forms most of the clots is either a late syn-sedimentary deposit, or is a neomorphic recrystallisation product replacing the primary sediment forming the clot during very early diagenesis. In addition to the trapping and binding processes interpreted to have formed the crinkly laminites, the clots mesoclots and columnar stromatolites are interpreted to result from the organic growth of a microbial ecosystem. The depositional environment is interpreted to be shallow subtidal to intertidal. |
| **Facies C2**   | Thrombolite clotted texture with layered and domal “stromatolite form” mesoclots (block 6, 21°21'20.64"N, 57°11'55.34"E) | This organisation into thicker and thinner layering indicates a control on growth rate of the thrombolite that has two main frequencies, a higher frequency that separates each lamina or mesoclot from the “matrix”, and a lower frequency that separates composite bands of mm-scale laminae and matrix from composite bands of cm-scale mesoclots and matrix. The strings of laminae, clots and mesoclots with mm to cm layering, compose successive layers of thrombolite growth. The irregular shape of clots and the varying thickness of laminae indicate a biological growth origin of individual clots and layers (or mesoclots), as opposed to deposition from suspension fall-out or chemical precipitation. The 1 mm to 5 cm scale double cyclicity is suggestive of tidally controlled double cyclicity and may suggest tidal controls on the growth of these thrombolites (semidiurnal, neap-spring, or solstice-equinox) or if not at least some sort of seasonal variation in growth rate. These facies are interpreted to have been laid down within the intertidal zone. |
Table 3 (continuation)

| Facies | Name and Depositional Environment | Interpretation of Facies in Terms of Depositional Processes and Environment |
|--------|----------------------------------|-----------------------------------------------------------------------------|
| Facies E1 (Figure 12) | Thrombolite, clotted texture with scour and growth Shallow intertidal | The lateral discontinuities within the layered thrombolite are interpreted to be the result of erosional scour followed by further thrombolic growth. In the exposure of block 4, lying 100 m to the west of block 6, associated features comprise metre-scale channel scour cutting into the layered thrombolite facies (see depositional geometries). This is more of a "scour and drape" or "scour and growth" than a "scour and fill structure". The evidence of scouring followed by renewed growth of thrombolite, denuding the scoured surface, indicates higher energy environment and stronger current action, presumably in a shallower intertidal zone than that of the mounded to columnar stromatolites and layered thrombolites lower in the section. |
| Facies E2 (Figure 13) | Massive thrombolite, homogeneous, clotted texture Higher energy beach ridge | The position of this massive rather featureless facies of varying thickness in the upper part of the shallowing cycle indicates deposition in fairly shallow water. The rather breccia-like aspect of the thin-section as well as the homogeneous nature of the deposit both indicate a possible initially loose grainy carbonate gravel or sandy sediment, as opposed to a bindstone such as the other thrombolite facies below. The wavy upper surface was clearly a depositional feature since the growth of the digitate thrombolite above radiates at right angle away from the surface. The bedforms must, therefore, have been bounded, or with smooth elongated ridges or waves, possibly indicating megatidal-size bedforms of a grainy sediment. |
| Facies F (Figure 14) | Digitate radiating thrombolite or bushy thrombolite Shallow lagoonal or salina | The branching of the bushy thrombolite mesoclots, building outwards and away from the substrate, is an organic growth form but the circular cross section is not conclusive of a microbial form; the framestone structure might suggest the form of a branching organic precursor (possibly a demosponge since biomarkers of these are recorded in Aas Group oils by Love et al., 1999). The infilling of erosive-base channel features (filling these erosive geometries from the base and from the side) indicates high energy (scouring) at least immediately prior to the thrombolite growth, but then the growth up to a terminal flat and extensive surface and lack of reworking or debris, would indicate low-energy conditions with little to no scouring or reworking up to the emersion. |
| Facies G1, G2, G3 (Figure 15) | Capping facies on bushy thrombolite Supralatal sabkhas | The three facies that lie directly on, or fill fractures in the bushy thrombolite provide clear evidence of deposition above sea level (supratidal), weathering, early lithification, karst, and transgressive flooding with infilling of "neptunian dykes". The microbreccia veneer on the bushy thrombolite (Facies G1) is typical "caliche" breccia produced by weathering of an emergent surface. The cement-filled and sediment-filled fractures (Facies G2) are interpreted respectively as karst (under the overlying evaporite deposits) and as neptunian dykes (fractures in lithified substrate infilled by grainy transgressive deposits). The dolomitised fine to crinkly laminites (Facies G3) is a dolomitised microbial mat deposit overlying a lithified and fractured thrombolite substrate. This surface was lithified and fractured (neptunian dyke) before deposition of the next layer (transgressive sediments). |
| Facies H1, H2 (Figure 16) | Dolomites and evaporites Inter-supratidal sabkhas | The thin-bedded dolomites and evaporites represent sabkha-type inter-to-supratidal facies, deposited at cycle tops following emersion. The brecciated facies is interpreted to have formed during subsequent intrastratal dissolution causing collapse under the weight of overlying sediments. |
| Facies I (Figure 17) | Finely laminated, partially silicified carbonates Low-energy shallow marine to intertidal | These laminated carbonates are stromatolites formed as a smooth to hummocky mat in a shallow-water to intertidal, low-energy environment, possibly under some wave influence. The regular darker and lighter laminae may result from an original difference in grain size and/or in mineralogy, and perhaps a difference in content of organic matter. The patchy silification could be linked to an evaporite-influenced diagenesis. The position directly overlying the evaporites, and the gradual transition to subtidal crinkly laminites above, suggest that this facies develops during transgression over a previous cycle. |
thus “condensing” the sedimentary record at least fivefold (from > 50 m high depositional profile to < 10 m thick stratigraphic section). Given the repeated drawdown in sea level that is necessary to explain the stratigraphy of the Ara evaporite basin with at least six successive carbonate platforms each encased in evaporites (Peters et al., 2003; Amthor et al., 2005; Al-Siyabi, 2005), a thinner sequence caused by concomitant sea-level fall is not an unreasonable hypothesis.

An alternative, slightly different scenario would not involve the possible link between Facies A1 and A2, but would emphasize the passive infill nature of the bushy thrombolites that build up to the emersion surface and sabkhas. In this view (Figure 27b), much of the laminate section could be composed of shallow subtidal to intertidal deposits (particularly the layered thrombolites with the tidal signature of double cyclicity). The channels and scours would be tidal drainage runoffs, and the bushy thrombolites would record a low-energy lagoonal or salina deposit.

In the second scenario, only the shallower portion of the full sabkha to basin depositional profile would be represented, so that this could be thought of simply as an image of greater detail on the littoral zone of the first scenario. However, one inference from the second scenario would be that the Qarn Alam Ara facies might represent a marginal to littoral setting with crinkly laminates and layered thrombolites deposited on extensive tidal flats and in lagoons or salinas. This could be the slightly different record coming from a unit at the base or at the top of a better-developed stringer platform, which could explain some of the discrepancies with regard to the platform to basin interpretation of the first scenario.

**High-resolution Stratigraphy, Cycles, Genetic Units and Stacking Patterns**

The 2–10 m thick high-frequency cycles show predominantly shallowing-up, progradational facies successions (Facies A to H), with thin caps of deepening aggradational tendency (Facies I). The package of a shallowing and then deepening succession indicates a unit of decreasing followed by increasing accommodation. Each progradational-aggradational unit represents a stratigraphic genetic unit (Busch, 1959). In so far as stratigraphic continuity is preserved over a number of genetic units, (albeit with a shift in facies tracts from one unit to the next) and as long as the depositional system does not undergo an abrupt major change in type, then the variations in accommodation from one genetic unit to the next will create a logical stacking pattern (seaward- or landward-stepping, or vertical stacking), with consequent preservation of progradational and aggradational half-cycles of genetic units (Homewood et al., 2000).

Since the deposition (in terms of facies) and preservation of a facies succession depends on the position of the section with regard to the depositional profile, we do not attempt to fit different cycles to a notion of a single “type cycle”, but rather we use the different facies successions (either in continuity or separated from each other) to reconstruct the depositional profile and the seaward or landward shifts indicated by the progradational or aggradational half-cycles (Homewood et al., 1992; Cross and Homewood, 1997). This approach has been carried out successfully in Phanerozoic carbonate and mixed systems (e.g. Homewood and Eberli, 2000).

At Qarn Alam, the separate blocks of Ara facies show different stratigraphic sections, with stacks of 1 to 3 cycles. The cycles are composed of facies successions that are similar to the type section of block 6, but are more or less complete, below the evaporite-dolomite white band that is always present in one form or another. The cycles differ mainly by the progressive lack of lower facies A2 (planar laminites), B (crinkly laminites) and C (crinkly laminites with incipient clotted textures).

The section exposed on the western face of block 6 conveniently provides the most complete succession of facies of a progradational cycle from deeper shoreface or subtidal through the shallower shoreface and intertidal zone, to a well preserved cycle top (Figure 28a). For present purposes this represents a more complete cycle with which other, less complete cycles may be compared in order to evaluate their respective positions along the depositional profile. The thicker cycle on block 6 (with more facies preserved) is overlain in continuity (above the partially silicified fine stromatolites, Facies I) by a new cycle of crinkly laminites (Facies B), then by crinkly laminites with incipient clotted texture (Facies C) and layered thrombolites (Facies D). The basal planar laminites with mudstone beds (Facies A) are missing here at the base of the upper cycle.
The three cycles exposed on the summit and eastern flank of block 4 (Figure 28b) are thinner than the more complete cycle, show less complete successions, have thinner layers of digitate thrombolite, and successively less preservation of both laminites (lower part of the type facies sequence), as well as less of (to none) of the evaporites capping the cycles. However, the upper cycles on block 4 show neptunian dikes as 50 cm deep grainstone-filled fractures, and grainstones directly capping the thrombolites, clear evidence of transgressive ravinement directly over the bushy thrombolite after karst and early lithification.

The three cycles exposed on block 4 (Figure 28b) are successively thinner from one to the next in stratigraphic order, and contain successively less of the lower facies types when compared with the more complete cycle on block 6. This is a clear stacking pattern, with a stratigraphic pattern
Figure 29: Schematic representation of cycles and stacking pattern at Qarn Alam. The same depositional profile is repeated first in a seaward and then in a landward stacking pattern. From green to blue to darker blue (A, B, C) the pattern is seaward stepping. Then yellow and red are landward stepping. At the profile location (between the two vertical black lines) the resulting stratigraphic succession of units A, B, C and D become thinner and base-truncated. A last veneer of transgressive deposits (Unit E) covers unit D and fills neptunian dykes with grainy material.

of progressive “base-cut-out” of facies, and this allows to reconstruct a model of seaward-stepping progradation under progressively decreasing accommodation, followed by a turn around to a major transgressive shift and a landward-step. The section above the third cycle is tightly refolded so that no further tendencies in stacking may be observed.

The lower cycle on block 4 is already thinner than the more complete cycle of block 6, and planar laminites with mudstone beds (Facies A) are not observed here. Since the stratigraphically continuous section starts from a structural contact (an oblique low-angle shear plane) it is not known as to whether the section was originally similar to the fuller section on block 6, or already base-truncated. All the same, this allows the reconstruction of a composite stacking pattern, seaward stepping and then a landward step, from the combination of blocks 4 and 6 (Figure 29).
BUSHY THROMBOLITES, PRIMARY DOLOMITE, FRACTURES, CEMENTS AND EARLY VERSUS LATER DIAGENETIC PHASES

Bushy Thrombolite Development, Organic Growth and Cementation

The thrombolite facies (Facies C, D, E and F, Tables 1, 2 and 3) show a transition from laminated to clotted textures (Kennard and James, 1986; Grotzinger, 2000; Grotzinger et al., 2005) with stromatolitic, layered, massive and dendrolite fabrics (Riding, 1999, 2000, 2011). Although the bushy thrombolites (Facies F, Plate 1) have a fabric similar to that of dendrolites, they are not built by a simple primary fabric of calcified microbes. The bushy, dendrolitic mesoclots do not show any skeletal or stromatolitic features, or any features of disturbance or bioturbation of a previous stromatolitic fabric. These arborescent structures are preserved by a complex record of infill within the empty, tubular cylindrical mould of a precursor form. However, no remains of any precursor (apart from the bushy mould) have been observed.

The lack of any mineralised wall, or mineralised primary internal fabric, or calcitised framework that would have given strength to the arborescent growth implies that the surrounding microcrystalline dolomite must have developed as a primary deposit, before the rotting away of an organic precursor in order to preserve the mould. The presumed organic growth form and the surrounding dolomitic matrix both may have fully developed together before rotting away, or there may have been an on-going process during sedimentation of organic framework growth, biomineralisation of the matrix (dolomite and clay minerals) and rotting away of the precursor. In any case, emplacement of the mould infill occurred after development of the first growth structure but before any fracturing and early diagenetic cementation. The earliest, hairline fractures cut across both the matrix and the calcitic infill of the mesoclot mould. The local occurrence of matrix-like finely crystalline dolomite in some places within the mould infill suggests that this was all going on more or less at the same time, as the sediment aggraded and filled the lagoon or salina. Plate 1 provides plane and cross-polarised microscope images as well as cathodoluminescence images. This plate illustrates the observations that have led to the following interpretation for the bushy thrombolites, with seven steps of development of the infilled and then fractured mesoclots:

1. Growth of an organic precursor and biominaleralisation of a contemporaneous dolomitic matrix surrounding the organic framework (Plate 1: A, F1).
2. Progressive rotting away or microbial digestion of the organic precursor to leave an empty mould as cylindrical voids within the dolomitic matrix (Plate 1: A, F2).
3. Crystallisation of aragonite needles within the void space as randomly oriented freely growing needle-like clusters (Plate 1: B, F3).
4. At the same time or after step 3, development of a dull to non-luminescent biominaleralisation of clotted calcite, together with accumulation of minor amounts and strings of microcrystalline microbial dolomite similar to the matrix (Plate 1: B, F4). The calcitic clotted phase is similar to the clots and mesoclots of the other stromatolites lower in the shallowing-up cycle.
5. Crumbling or early irregular brittle fracturing both of the digitate mesoclots and the surrounding matrix (Plate 1: C, F5).
6. Chemical precipitation of finely zoned calcite cements (Plate 1: D, F6). Neomorphic recrystallisation of the clotted calcite may have started at this step.
7. Fractures partially filled with calcite cements (Figure 15d, Plate 1: E, F7) cut both mesoclots and dolomite matrix, and therefore are showing clear evidence of the early origin of phases 1 to 6.

Fractures

Multiple generations of fractures are conspicuous at the outcrop scale, with recent large open fractures causing instability of the rock face (Figures 26 and 30a). Even otherwise undeformed packages of strata show numerous open fractures and several generations of earlier fractures (Figure 30a). In general, early fractures may be tightly cemented or may have some residual open porosity, whereas late fractures are open and not cemented at all (Figure 26). These open fractures
A1: Thin-section view of section across a digitate mesoclot. Strands and patches of microcrystalline dolomite (1b) similar to the matrix are seen within the neomorphic calcite spar.

A2–A3: Same view in cathodoluminescence. Image shows that the original material has been replaced by a sinuous band of dull luminescent clotted calcite (1a) phase similar to other thrombolitic clots; growth of acicular needle shaped crystals with an aragonite habit that have been subsequently leached and partly infilled by a dull luminescent clotted calcite fabric, whereas the acicular form is outlined by brightly luminescent calcite, and early diagenetic cements (see Plate 1B and 1D).

B1: Needle shaped acicular crystals (arrow, 2b) suggestive of aragonite. The crystal form has been leached and replaced by brightly luminescent calcite coating a dull luminescent clotted phase (1a) similar to that of other clots and mesoclots (see D). Strands and patches of microcrystalline dolomite (1b) similar to the matrix are seen within the neomorphic calcite spar.

C1: Thin-section under plane polarised light; neomorphic spar has overgrown calcite mesoclots and early diagenetic cements while microcrystalline dolomite matrix is preserved.

C2: Same field of view as C1. Brightly luminescent phase 2b runs into hairline fractures (white arrows), caused by crumbly breakage of the phase 1a mesoclot calcite. Phase 3 cements (non-luminescent cement) fill later, wider fractures that may be lined first by bright phase 2b cement, or not. See also Plate 1F.
D1: Thin-section, plane polarised light: crude blocky fascicular optic neomorphic spar of the calcite mesoclots (inclusions of microcrystalline dolomite) and cements, surrounding microcrystalline dolomite of the matrix (1b).

D2: Same field of view as D1 (cross-polarised light) with the contour of cements on the mesoclot as revealed by cathodoluminescence (D3, D4) traced in blue.

D3: Cathodoluminescence image, same field of view as D1, D2.

D4: Same field of view as D3.

D5: For location see white rectangle on Plate 1A1, 1A2. Crossed-polarised light, neomorphic spar has overgrown calcite mesoclots and early diagenetic cements while microcrystalline dolomitic matrix is preserved. Cements are growing in optical continuity with earlier phases.

D6: Same field of view as D5, cathodoluminescence image.

D4 and D6, simplified cement stratigraphy shown by luminescence and cement phase contacts.
1: mesoclot and matrix: 1a dull clotted fabric of calcite mesoclot; 1b reddish luminescence of dolomitic matrix.
2: early cement phase: 2a dull brown; 2b bright yellow to orange; 2c dull brown: (D6, same location as D5).
3: subsequent dull to non-luminescent cement in two stages: 3a, 3b, separated by a thin violet luminescent fringe.

The phase (2b) also replaces needle shaped crystals with an aragonite habit (see Plate 1B).
E1 and E2: Later fracture cutting clotted calcite and dolomite of stromatolitic thrombolites. The fracture is lined on both sides, in places, by the brightly luminescent phase 2b calcite cement (central part of image, white arrow) and the fracture is filled by dull to non-luminescent phase 3 calcite cement.

Plate 1F: Schematic representation of the seven stages of mesoclots development and subsequent syn-depositional replacement.

1. Growth of an organic precursor and biomineralisation of a contemporaneous dolomitic matrix surrounding the organic framework.
2. Progressive rotting away or microbial digestion of the organic precursor to leave an empty mould as cylindrical voids within the dolomitic matrix.
3. Crystallisation of aragonite needles within the void space as randomly oriented freely growing needle-like clusters.
4. At the same time or after step 3, development of a dull to non-luminescent biomineralisation of clotted calcite, together with accumulation of minor amounts and strings of microcrystalline microbial dolomite similar to the matrix.
5. Crumbling or early irregular brittle fracturing both of the digitate mesoclots and the surrounding matrix.
6. Chemical precipitation of finely zoned calcite cements. Neomorphic recrystallisation of the clotted calcite may have started at this step.
7. Fractures partially filled with calcite cements cut both mesoclots and dolomite matrix, and therefore are showing clear evidence of the early origin of phases 1 to 6.

Legend for thin-section images and schematic diagram

- PL = Plane polarised light
- PX = Cross-polarised light
- CL = Cathodoluminescence

- 1a = Biomineralised calcite (dull luminescence, clotted fabric)
- 1b = Biomineralised dolomite (reddish luminescence, microcrystalline fabric)
- 2a = First early cement phase (dull brown luminescence)
- 2b = Second early cement phase (bright yellow to orange luminescence)
- 2c = Third early cement phase (orange to dull brown luminescence)
- 3a = Later cement phase (dull to non-luminescent)
- 3b = Last cement phase (non-luminescent)
Microbialites of Qarn Alam, Oman appear to be a late phase of breakage linked to the unroofing and decompression of the structure (Reuning et al., 2009). Fairly randomly oriented polygonal fractures disrupt slabs at the margins of the blocks and rafts (Figure 30) and are injected by the matrix of the diapir (predominantly gypsum Figure 30b, c, d). Together with the breccias and injections at the margins of the blocks and rafts, these fractures were clearly caused during structural deformation from halokinetic movement of the diapir. Cement types and generations linked to early and later fracture filling are described and interpreted below.

The blocks and rafts also show shear planes cutting across the bedding at low angles (Figure 30e) as well as tight to isoclinal refolding. This deformation is related to the diapir evolution (Reuning et al., 2009) and as a result stratigraphically coherent sections rarely measure more than 10 m in thickness.

Fractures partially filled with calcite cement cut both mesoclots and dolomite matrix of the bushy thrombolites as well as the stromatolitic thrombolites and the laminites. Petrographic relationships between fractures and fracture-fill cements with the clotted fabrics and the early phases of cement that cover them are described below. These relationships are best illustrated in the bushy thrombolites, and allow establishing a chronology of primary deposits, early fractures, early cements as well as later fractures with cement fills, before the latest open fractures described above.

Cements and Early versus Later Diagenetic Phases

The nature of the facies, facies sequences, cycles, and genetic units, together with their sedimentary petrography give a clear pattern of syn-depositional to very early diagenetic features. But the recrystallisation of various phases (the mesoclots in particular) to optically orientated, more or less fascicular if somewhat blocky calcite (Plate 1) raises the question of the degree of chemical modification during diagenesis, and so also questions the diagenetic timing of various phases of fracturing and cementation (Folk, 1965; Bathurst, 1975). The cement stratigraphy is most well developed and differentiated in the bushy thrombolites, with three main generations of cements, comprising several subsets, and that are separated by surfaces that show truncation in some places but apparent continuity at others.

The earliest chemical replacement precipitate (but not yet a proper cement) is composed of the fine needles and clusters with an aragonite habit that grew in the branching mesoclot voids of the bushy thrombolites, after (or even during?) the removal of the primary organic growth material (Plate 1: A2, B1). Since these needle clusters are intergrown with a clotted calcite fabric (and a very minor amount of microcrystalline dolomite) to complete the infill of the digitate growth framework, the needle clusters must represent a syn-depositional precipitate. This most probably aragonitic phase was subsequently replaced by the brightly yellow luminescent calcite phase, a replacement following leaching and dissolution of the aragonite.

Both laminites and thrombolites facies show a first generation of cements that coat the clotted fabric of both microbial calcite (Plate 1: 1a) and dolomite (Plate 1: 1b). These cements start with a very dull to dark brown zoned coating of botryoidal to idiomorphic stubby crystal habit, which progressively develops planar crystalline faces over the growth of one to four darker and lighter zones, each made up of several finer layers (Plate 1: 2a). Following this very first cement, a brightly yellow to orange luminescent idiomorphic zoned calcite cement is observed in all four microbialite facies (Plate 1: 2b). This conspicuous cement either grows in continuity from previous dull facets or cuts across the earlier cement, replaces the aragonite-habit needle clusters, fills fine hairline fractures cutting across the clotted microbial calcite or dolomite, and most obviously coats individual calcite clots or clumps of clots along irregular finely sutured contacts (Plate 1: A, B, C2).

The hairline fractures show random orientation and connect to the sutured contacts between clumps of clots. Microstylolites that are more or less bedding parallel in both the planar and the crinkly laminit facies pass laterally to fine fractures or pore space that are also cemented by this brightly luminescent phase.
Figure 30: Fractures and shear plane.
(a) Open fractures presumably caused during late-stage decompression. These cause rock fall and progressive collapse of the rocky hill.
(b) Polygonal fracture pattern on the bedding surface at the base of block 6. The gypsiferous conglomerate behind the 15 cm pencil is the matrix of the diapir. 
(c) Cemented fractures and brecciation, planar laminites (Facies A2) block 6. 
(d) Partly cemented fractures with residual vuggy porosity, planar laminites (Facies A2) block 6. 
(e) Shear plane cutting stratification at a low angle, block 4.
After the early cements, larger and more penetrative later fractures, partially cemented by non-luminescent calcite, cut indiscriminately across mesoclots and matrix (Plate 1: E and F7). In places these fractures follow earlier hairline fractures for some way, leaving a thin band of brightly luminescent cement along one or both of the margins lining the later fracture (Plate 1: E).

Stable Isotopes

A plot of the $\delta^{13}C$ and $\delta^{18}O$ values from microdrilled samples of type section, block 6 is illustrated on Figure 31. The green data points are from Al Balushi (2005), and they are from small bulk samples obtained by hand-held drilling on the outcrop with a 2–3 mm diameter drill bit. These samples were taken for study of the isotope stratigraphic record (Al Balushi, 2005) knowing that the Ara stringer 4 (A4C) in the SOSB contains a -4‰ $\delta^{13}C$ excursion that marks the Proterozoic/Phanerozoic boundary (also known as Precambrian/Cambrian boundary, PCB, Ediacaran/Cambrian boundary) (Amthor et al., 2003).

Isotope values for calcite and dolomite throughout the whole section (ignoring late fracture fill cements) show a limited range between +2‰ to +4‰ for $\delta^{13}C$, and a slightly broader range between +0.5‰ to -5‰ for $\delta^{18}O$. Note that even with the microdrill procedure, the early, dull to brightly luminescent cements, aragonite replacement and hairline fracture fills are too finely intermixed within the mesoclot calcite to be analysed separately. Later fractures are sufficiently large to allow separate sampling (Plate 1: E), and these show entirely different values with $\delta^{13}C$ in the range of -2‰ to -6‰, and $\delta^{18}O$ from -7.5‰ to -11‰ along a covariant trend that is generally considered to be an indication of a diagenetic signature (Allan and Matthews, 1982). The isotopic values of $\delta^{13}C$ and $\delta^{18}O$ for the clots, clumps of clots and mesoclots (together with the early cements) show no such covariant distribution, but remain at constant positive $\delta^{13}C$ values with limited spreads of $\delta^{18}O$ for each individual component.

When plotted against the type section log (Figure 31a) the distribution of the values of $\delta^{13}C$ and $\delta^{18}O$ for the microbialites does provide a striking confirmation of the preservation of values close to primary and syn-depositional to very early diagenetic compositions. The successive facies from laminites to thrombolites show a similar broad spread of $\delta^{18}O$ for calcite in the successive facies from A to H, between -1.4‰ and -4.9‰, although values for the finer clots and clumps of clots in the stromatolitic and layered thrombolites are grouped a little closer and the values for the mesoclots of the bushy thrombolites are a little more spread out. As for the values for the later fractures, these much lighter $\delta^{13}C$ and $\delta^{18}O$ signatures do provide a check on the lack of resetting of the composition of the primary phases throughout the section.

DISCUSSION

The most striking aspect of the microbialites of Qarn Alam must be the remarkable preservation, not only of individual microbial fossils and textures but in particular that of mineralised EPS or EPS template structures, in these ca. 540 Ma old carbonate rocks that are entombed in such a complex structural setting (sheared and folded blocks in a surface-piercing salt dome). The preservation of syn-depositional and very early diagenetic cements and microbial fabrics reinforces the interpretations made here.

Sedimentology and Stratigraphy

The two contrasting depositional models that have been presented (Figure 27a, 27b) are built from the facies associations and sequences at Qarn Alam and they do differ in at least two significant ways: to start with, the depositional environment. The first model (similar to that of the Ara carbonates of the SOSB; Al Balushi, 2005; Al-Siyabi, 2005; Pope et al., 2000; Schröder et al., 2005) places the laminites in deeper water environments. As commented on in the introduction, a major argument for this deeper water interpretation (as well as the cycle thickness, facies associations and successions in the SOSB) came not only from observations on core from the Ara Formation in the SOSB, but also from observations made on late Proterozoic Nama Group carbonates in Namibia. In both cases, there is strong to irrefutable evidence of deeper water settings for the deposition.
Figure 31: Neoproterozoic stable isotopes of oxygen and carbon. (a) Stable isotope values (from microdrill on thin-sections or plugs) in stratigraphic context. Note that the $\delta^{13}C$ values remain fairly close between $+2\%_o$ and $+4\%_o$. The $\delta^{13}C$ reference is therefore repeated at each stratigraphic level. The $\delta^{18}O$ shows stronger variations from $+0.3\%_o$ to $-5\%_o$, with a clear distribution of the different lithologies. The lack of resetting of the stable isotopes in these separate layers is evident (see commentary in text and in the Discussion section). (b) Cross plot of $\delta^{18}O$ and $\delta^{13}C$ from microdrilled samples; rectangle shows zone of stable isotope values of C and O in equilibrium with Neoproterozoic seawater, from Derry et al. (1992) and Jacobsen and Kaufman (1999) as shown in Reuning at al. (2009); violet arrow shows trend of values influenced by syn-depositional evaporitic conditions; blue arrow shows trend of values influenced by syn-depositional to early diagenetic freshwater influx and mixing of early diagenetic cements with mesoclots during sampling; orange arrow shows trend to more strongly negative isotopic values of later diagenetic cements.
of several laminitic facies (Saylor et al., 1995; DiBenedetto and Grotzinger, 2005; Al-Siyabi, 2005; Schröder et al., 2005). In the second model proposed here, the laminites are interpreted to be mostly intertidal to shallow subtidal, comparable to microbial flats of Abu Dhabi (Bontognali et al., 2010; Strohmenger et al., 2011), in keeping with the limited thickness of section from laminitic facies to caliche and emersive facies, as well as with regard to the potential tidal indicators in the layered thrombolitic facies (see Table 3, Facies D). A notable difference between the laminites of the Qarn Alam Ara facies and those of the SOSB Ara deposits is their organic content. Whereas the subsurface Ara deposits are characterised by organic-rich basinal crinkly laminites (Al-Siyabi, 2005; Schröder et al., 2005) the Qarn Alam shallow-water laminites are very poor in organic content (< 0.1%) as described above. In spite of the supposedly organic-rich nature of the Qarn Alam laminites according to Dunham (1955), the TOC content of these laminites in fact is negligible.

A second difference between the two depositional models for the Qarn Alam Ara facies lies in the paleogeography and the stratigraphic setting. The earlier model (Al Balushi, 2005; Al-Siyabi, 2005) places the laminitic-stromatolite-thrombolite facies association towards the shelf-slope break on a platform to basin depositional profile whereas the alternative model presented here places these facies associations at a marginal, tidal flat to lagoonal or salina location. In the case of the second model, the paleogeographic and the stratigraphic settings would be quite different from the platform-ramp-pinnacle reef settings suggested by figure 29 of Al-Siyabi (2005, p. 67). In terms of paleogeography, as opposed to one or the other of the SOSB settings of the Ara models, the Qarn Alam Ara facies could correspond to a marginal marine setting. Compared to the SOSB stringers, the Ara facies might come from the base, the top or at the margin of a similar stringer platform, given the marginal association as opposed to that of a fully developed carbonate platform and deeper basin. The differences between the Qarn Alam microbialites and the SOSB stringer facies may just typify differences between the Ara Formation deposits coming from the Ghaba Salt Basin and those of the South Oman Salt Basin.

In terms of stratigraphy, the bulk sediment stable isotope record (Al Balushi, 2005) does not correspond to the A4C stringer (characterised by a negative δ13C excursion at the Proterozoic-Phanerozoic boundary; Amthor et al., 2003). Since no late Proterozoic Namacalathus and Cloudina fossils have been observed either, the Qarn Alam rocks are likely to be younger than the A4C, so Ara A5 age or even younger (Al Balushi, 2005). Perhaps the laminites and thrombolite facies of Qarn Alam are less similar to the now classical SOSB Ara facies than was previously thought, and perhaps there are slightly different reservoir models for some of the Ara of the SOSB waiting to be developed. This would be compatible with some recent exploration results that seem less well accounted for by the classical models (personal comm. Gregory Stone, PDO Muscat Oman, 2013).

Microbialites, Primary Dolomite and Microbial Fossils

The debate over microbial versus chemical growth for stromatolites of Proterozoic age has been firmly established (Grotzinger and Rothman, 1996; Grotzinger and Knoll, 1999; Pope et al., 2000; Riding, 2011), with the conclusion that form alone cannot differentiate between biogenic and abiogenic growth. Numerical simulation of stromatolite and thrombolite growth produces close similarity between numerical model outputs and stromatolite and thrombolite morphologies (e.g. Dupraz et al., 2006). Many Proterozoic stromatolites are recrystallised or diagenetically altered such that it is not possible “to demonstrate the presence of textures uniquely attributable to the presence of microbial mats or biofilms…. due to an indecipherable level of diagenetic recrystallisation” (Grotzinger and Knoll, 1999).

In the case of Qarn Alam, the distinctive petrographic features described in the previous chapters (under cathodoluminescence in particular) make it easy to identify the microbial fabrics both in laminites and thrombolites, whether calcite clots, clumps of clots or mesoclots, or the microbial microcrystalline dolomitic matrix in the thrombolites. Where the microcrystalline dolomite matrix is concerned, as already discussed, this is clearly a primary deposit, and not a diagenetic product. The microbial fossils and textures described above in the laminites and thrombolites add a record of forms to the well-established record of Ara Group biomarkers from diverse Proterozoic microorganisms in pelagic and benthic niches (Summons and Walter, 1990). The petrography
of the bushy thrombolites clearly shows a multiphased record of growth, biomineralisation with primary dolomite and cement precipitation. The digitate, branching mesoclots do not preserve any record of the original organism other than the general external dendrolite-like morphology. There is no stromatolitic morphology (layering, lamination) to be found with the framework and it is not comparable with regular cylindrical tubular stromatolites (tubestones and tube-hosted stromatolites) described in somewhat older Neoproterozoic Cap Carbonates by Bosak et al. (2013). The lack of primary biomineralisation suggests a significant difference between the Qarn Alam dendrolite-like forms and recent descriptions of dendrolites and thrombolites (Riding, 2000, 2011). Biomarkers of demosponges are abundant in all formations of the Huqf Supergroup and have been found in the Ara oil of the South Oman Salt Basin (Love et al., 2009), however no sponge or demosponge macrofossils have been reported so far in rocks of this age. It would not be surprising therefore that the bushy structure could be a macrofossil trace corresponding to the demosponge biomarkers of Love et al. (2009) that are so abundant. Since no tissues have been fossilised within the structure this remains purely speculative.

The classically microbial clotted fabrics (e.g. Flügel, 2010; Riding, 2000) are associated with microbial fossils of various types (both filamentous and coccioid) as well as with mineralised microbial EPS at Qarn Alam. In the planar laminites, rod-shaped fossils are closely comparable with calcite-mineralised microbial forms in recent deposits of Eleutheria, Bahamas (Glunk et al., 2011). As for the calcite microbial fossils in the crinkly laminites, comparison of filaments and anhedral calcite clusters of Qarn Alam can be made with illustrations in Noffke et al. (2003, their figure 1). Concerning the bushy thrombolites, mineralised EPS is common in the dolomite lithologies although other fossils comprise micron-size coccioid forms (both individual and linked), which have been found in the calcite lithologies at Qarn Alam.

Slightly recrystallized calcite fabrics in the planar laminites of the Ara facies resemble the progressive calcite mineralisation of EPS (Dupraz et al., 2004; Bontognali et al., 2010, their figure 2.10). Bontognali et al. (2010) make it clear that mineralised EPS alveolar structure should be taken as the consequence of microbial activity and therefore provides a distinctive microbial fossil. The dolomite biomineralised alveolar fabrics of Qarn Alam may be compared with cryo-SEM images of EPS of Abu Dhabi (Bontognali, 2008, figure 10A p. 837). The enigmatic “horseshoe shaped” calcite fragments of the planar laminites, with their curved and rounded forms are not simple crystal growth, but appear to be fragments broken from a biogenic structure such as the air dried, slightly calcified mucus sheaths illustrated by Kazmierczak et al. (2011, their figure 13). The bundles of fibrous clay minerals intimately associated with the biomineralised alveolar fabric may be compared with SEM images of similar features in Abu Dhabi sabkhas illustrated by Sadooni et al. (2010, their figure 3C).

**Syn-depositional Cementation and Early Diagenesis**

The early cement phases that follow and seal the microbial fabrics at Qarn Alam are strikingly similar to the Holocene beachrock cements from Togo, described and analysed by Amieux et al. (1989). No analyses have been made yet to identify element activators, inhibitors or quenchers of luminescence (Machel, 2000) but the initial dull to low luminescent cements could indicate a vadose marine (intertidal) to phreatic marine (subtidal) environment. The second, brightly luminescent cement (probably Mn++ activated) following slight leaching and dissolution of aragonite, could represent the influx of mixed fresh and marine waters, and the third dull to non-luminescent cement might result from freshwater invading the freshly indurated sediment in the continental phreatic zone as the depositional system prograded seawards (Amieux et al., 1989). The stable isotopes of the neomorphic mesoclots do show a shift to lighter values, and this supports the interpretation of freshwater influence. Although the crystal habits of calcite in the mesoclots and clots of the Ara facies show neomorphic recrystallisation (Folk, 1965), the later fabric does not show any concomitant chemical overprinting or replacement of the primary fabrics when seen under cathodoluminescence. In fact, the cements in the bushy thrombolites show less modification than do the Togo examples. The close comparison and similarities between the Qarn Alam microbialites and these Holocene beachrock cements in Togo suggest that the syn-depositional to very early diagenetic cements of the laminitite-thrombolite sequence at Qarn Alam have been unusually well...
preserved. The preservation of primary cement chemistry is compatible with the definition of neomorphism by Folk (1965) but does not suggest an intermediate phase of liquid film during the neomorphic replacement of crystal orientation and habit (Bathurst, 1975) that would have tended to alter the primary features. The neomorphism that affects only the calcite in these microbialites would correspond to the “insignificant recrystallisation” of Machel (1997).

If the evidence were to be derived solely from thin-section petrography, it would be plausible to argue that early cementation occurred during the progradation and accumulation of a full shallowing-up cycle. Microbial controls on sedimentation were maintained during the deposition of a complete facies sequence, only to be followed at a later stage by early diagenetic cementation (Amieux et al., 1989). However, a different mode may be indicated by observation on the slabbed sample of columnar stromatolite heads of Facies C2 in the laminites-thrombolite transition zone (Figures 10, 11 and 21). The lamina by lamina, “layer by layer” mode of deposition, involving repeated cycles of deposition, cementation, erosion, and then deposition starting again, and suggests that the early cementation also occurred progressively during aggradation as the sediment sank below a certain biological/chemical threshold under fresh deposits. This cementation was presumably only centimetres below the surface, starting before but carrying on after crumbling of the sediment under a light load (syn-sedimentary cementation or syn-depositional diagenesis). The development of clusters of needle shaped crystals as a first infill phase in the bushy thrombolites (partially infilling the mould of an organic framework during or after removal of the digitate primary organic growth) may well represent a similar process to that described by Arp et al. (2003) and Arp et al. (2004) in the waters of increased alkalinity in Satonda crater lake. Arp and co-authors describe syn-depositional acicular aragonite clusters growing in “exopolymer-poor spaces” such as voids, lysed algal cells and inside sponge resting bodies.

The lack of separate isotopic analyses of each of the individual early cements compared to the clots, clumps of clots, mesoclots and dolomites, limits the interpretation regarding meteoric water influx. Obviously, the regular exposure of tidal flats and the complex interaction of meteoric and marine aquifers do not exclude one or the other of the hypotheses above (cementation layer by layer or only later, after deposition of a genetic unit). Thin-section staining and EDS analyses already indicate that there is neither Fe-calcite nor Fe-dolomite in the laminites or thrombolites, which suggests an oxidizing environment. The relationships between microbial communities, depositional environments, and the primary to early diagenetic mineral phases at Qarn Alam are addressed by Mettraux et al. (in press).

**Microbialites, Microbes and Microbial Communities**

The appearance of dolomite together with calcite clots as a microbial fabric in the shallower thrombolites, higher on the depositional profile than the limestone microbial laminites, suggests that the microbial ecosystem inhabiting the shallower water column and sediment was different compared to the ecosystem deeper in the water (or lower on the tidal flats), a variation possibly accompanying a change in seawater chemistry. This suggestion is reinforced by the development, still higher on the profile or more towards the land in lagoonal to salina waters, of a digitate organic possibly sponge-like organic form. This new member of the community accompanied the microbial primary-dolomite precipitating ecosystem, and was sufficiently competitive in growth compared to the surrounding microbial gel to maintain its morphology intact and distinct. However, the organic form rapidly rotted away, providing a void to be filled first by clusters of aragonite needles and then by a microbial community precipitating mostly calcite with some microcrystalline dolomite. The difference between the subtidal, lower intertidal and upper intertidal records might come from the microbial community structure and metabolic processes involved, but alternatively might just simply come from the effects of decomposition of a thinner or a thicker organic layer, and so resulting from the thickness of the mat or gel developed differentially in subtidal to intertidal settings.

This apparent tiering of communities, as well as the change from purely calcitic to mixed calcite-dolomite biomineralisation products, probably records the changing chemistry in fairly stratified waters, certainly of the salinity but possibly of oxygen concentration as well.
The depositional sequence of the Ara facies, from laminites to bushy thrombolites (capped by the caliche crust and evaporite layer) may have harboured successive different microbial communities. The trend from subtidal to intertidal to lagoon or salina depositional environments was accompanied by a gradient of increasing salinity, and degradation of microbial EPS would likely have been under more reduced conditions. In some respects the microbialite succession and the sequence of environments is quite comparable to the somewhat older Beck Spring thrombolites (Harwood and Sumner, 2011) although similar facies terms (e.g. bushy thrombolite) have not been used for similar features in the two cases. Certainly, as for the Beck Spring case, the thrombolite textures described here are not the result of colonisation and grazing over a surface microbial mat.

At Qarn Alam, microbial colonisation of sediment in the shallow subtidal to lower intertidal environment started with a tenuous biofilm (probably of cyanobacteria) that just covered the sediment surface, between the higher-energy events that brought in the grains. Fluorescence types and morphologies of this organic matter are suggestive of microbial EPS (Pacton et al., 2011; pers. comm. M. Pacton, 2013). A more substantive, thicker mat or gel developed in the intertidal environment. Here there appears to have been an alternation between the development of fine layers of cyanobacterial calcite clots and clumps of clots, and times of primary microcrystalline dolomite development. This alternation, which shows a clear double cyclicity in the thickness of successive layers of calcite and dolomite, may reflect a monthly to yearly variation in tidal regime (neap-spring, equinox-solstice etc.). The longer periods of flooding or submersion lead to mat development and calcitic microbial sediment (clots and mesoclots) whereas longer duration of exposure, desiccation and degradation of the EPS gel mediated dolomitic deposits. The dolomite (and accompanying dolomitic microbial fossilisation in the thrombolites) was more probably mediated by the degradation of microbial EPS rather than directly by microbial activity (pers. comm. T. Bontognali, 2013, according to experimental observations). Finally, the bushy thrombolites suggest the development of sponge-like organisms in salinas or saline lagoons, while the degradation of microbial gels surrounding the digitate organic forms mediated the dolomite matrix as salinity increased towards the top of the sequence. The calcite-clotted phase of the digitate mesoclot infill, following initial aragonite crystal growth, may have taken place with meteoric flooding of the cavities, or with subsequent seawater flooding.

Preservation of the Microbial Record

The extremely fresh aspect of the biomineralised alveolar EPS structures both in calcite and dolomite, the finely detailed preservation of micrometre or even finer scale mineral associations with little crystal overgrowth or recrystallisation imaged by the SEM, the limited cementation of vugs and fractures (open vugs are found in most of the facies but are larger and more common in the thrombolites), all point to an extremely limited flow of fluids after the syn-depositional to very early phase of cementation.

The good preservation of the bushy thrombolite framework, a mould passively infilled by clusters of aragonite needles as well as predominantly calcitic microbial fabrics, is one illustration of how little modification of primary sedimentary features has taken place, in particular from burrowing, reworking or other contemporaneous biological or physical processes. Callow and Brasier (2009) and Brasier et al. (2011) have emphasized the remarkable preservation of the fossil record across the Ediacaran-Cambrian interval, precisely the age of the Qarn Alam microbialites. They present a sedimentological-microbiological-geochemical model in which the lack of infaunal bioturbation is linked with microbi ally mediated, elevated ionic concentrations in pore waters at or near the sediment surface. These strong ionic gradients, preserved through lack of sediment mixing, would have “encouraged early cementation and lithification of sediments, often prior to complete decomposition of delicate organic structures” (Brasier et al., 2011). Although their model is mostly based on silicilastic cases, the sedimentological and geochemical features may be relevant here.

The zoned idiomorphic cements that coat the microbial fabrics in all the facies indicate a fairly abrupt change or rapid transition from microbial to chemical controls on sedimentation and early lithification protecting the microbial fabrics and fossils. The microbial dolomites (or very high
magnesian calcites) generally show less negative values of $\delta^{18}$O than the calcite, with even positive values from the caliche crust and the dolomites in the white band. There is a limited spread of $\delta^{18}$O values when taken separately for each of the biomineralised fabrics, and the whole spread is fairly constant throughout the shallowing-up cycle when plotted against stratigraphy (Figure 31b). However, each fabric has a fairly well defined field, apart from the mesoclots of the bushy thrombolites in which the mix (during sampling) of early diageneric cements and biomineralised clots is greatest. The data would indicate that no major diagenetic resetting of oxygen isotopes has taken place (Peter Swart and Gregor Eberli, pers. comm. 2012). The $\delta^{13}$C and $\delta^{18}$O for the dolomites, with little to no early cement included, are the closest to primary depositional values, and they show an evaporitic trend compared to Neoproterozoic seawater equilibrium values ($\delta^{18}$O -1‰ to -3‰, $\delta^{13}$C +2‰ to +4‰; Derry et al., 1992; Jacobsen and Kaufman, 1999; Bartley and Kah, 2004). The spread of values of the clots, the clumps of clots and mesoclots may well be explained by the incorporation of some amount of early cement with an isotopically lighter meteoric water influence (Allan and Matthews, 1982).

Fracturing during later burial or uplift (whatever the depth) was not accompanied by sufficient cementation to fill and occlude the fractures. The lack of fluid influx, which could have brought in significant quantities of diageneric minerals to precipitate cement or cause leaching, is probably best explained by the sealing effect of the evaporites in which the blocks and rafts now float. This would imply that the entrapment within the evaporites must have been maintained during salt dome structuring and burial, after the stratigraphic emplacement at the start.

CONCLUSIONS

The limestones and mixed limestone-dolomite lithologies of the Ara facies at Qarn Alam are conclusively shown to be predominantly microbial in origin, with a limited amount of syn-depositional to very early chemically precipitated cement. Filamentous and coccoid microbial fossils occur in both the limestones and dolomites, as do mineralised EPS alveolar frameworks.

Primary dolomite occurs in thrombolites mostly as a very fine to microcrystalline phase that forms a matrix around mesoclots and as irregular layers between clots and clumps of clots. This highly porous fabric shows no sign of recrystallisation or of post-depositional modification. The calcite clots, clumps of clots and mesoclots do show variable but limited recrystallisation but have retained isotopic signatures close to primary values in equilibrium with Neoproterozoic seawater. Later diageneric cements show much more negative $\delta^{13}$C and $\delta^{18}$O values than the microbialites and syn-depositional to early diageneric cements.

Planar and crinkly laminites have calcitic microbial fossils and calcite-mineralised EPS, whereas thrombolites have dolomitic or very high magnesian calcite microbial fossils and dolomite-mineralised EPS. The lithologies have different positions in shallowing-up cycles, and suggest that at least three different ecosystems colonised the depositional profile. A lower microbial community forming biofilms on the laminites (calcite producing), a second microbial community higher up with thicker mats and gels to form thrombolites (calcite and dolomite producing), and a third ecosystem towards the top with a possibly sponge-like non-mineralised organism growing together with the calcite and dolomite producing microbial assemblage.

Two alternative facies models illustrate the depositional environments interpreted from the Ara facies. A first model, similar to previous models, is built with the thrombolites as a high-energy facies separating deeper water laminites from peritidal to sabkha environments. A second model takes into account the relatively thin stratigraphic units with shallowing-up cycles capped with caliche and evaporites that indicate emersion. This second model places the laminites in shallow subtidal to intertidal environments, with the bushy thrombolites growing in low-energy lagoons or salinas along the littoral. Whereas the first facies model would be a close analog to the Ara stringers of the SOSB, the second model would show stratigraphic and paleogeographic differences with the classical SOSB case.
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