Microbial Carbonates in Space and Time: Implications for Global Exploration and Production

19-20 June 2013

Corporate Supporters

bp

Statoil

Conference Sponsors

Chevron

bp

BG GROUP

MAERSK OIL

BAKER HUGHES

PETROBRAS
## CONTENTS PAGE

<table>
<thead>
<tr>
<th>Section</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conference Programme</td>
<td>3 - 5</td>
</tr>
<tr>
<td>Oral Presentation Abstracts</td>
<td>6 - 81</td>
</tr>
<tr>
<td>Poster Presentation Abstracts</td>
<td>82 - 101</td>
</tr>
<tr>
<td>Fire and Safety Information</td>
<td>102 – 103</td>
</tr>
</tbody>
</table>
## PROGRAMME
### Wednesday 19 June

<table>
<thead>
<tr>
<th>Time</th>
<th>Session</th>
<th>Speaker</th>
<th>Topic</th>
</tr>
</thead>
<tbody>
<tr>
<td>08.30</td>
<td>Registration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>09.20</td>
<td>Welcome</td>
<td>Bernie Vining</td>
<td></td>
</tr>
<tr>
<td>09.40</td>
<td>Keynote</td>
<td>S. M. Awramik (University of California)</td>
<td>Microbialites through Space and Time.</td>
</tr>
<tr>
<td>10.10</td>
<td>Session 1</td>
<td>G. Winterleitner (Royal Holloway University of London)</td>
<td>3D Digital Reservoir Model of a Microbialite Reef in the Neoproterozoic Nama Group in Namibia.</td>
</tr>
<tr>
<td>10.35</td>
<td>Break</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.05</td>
<td>Session 2</td>
<td>J.E. Amthor (Petroleum Development Oman)</td>
<td>Ara Group Reservoirs of the South Oman Salt Basin: Isolated Microbial-Dominated Carbonate Platforms in a Saline Giant.</td>
</tr>
<tr>
<td>11.30</td>
<td></td>
<td>S. Becker (RWTH Aachen University)</td>
<td>Reservoir Quality in the A2C-Stringer interval of the late Neoproterozoic Ara-Group of the South Oman Salt Basin: Diagenetic relationships in space and time.</td>
</tr>
<tr>
<td>12.35</td>
<td>Lunch</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12.55</td>
<td>Posters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13.50</td>
<td>Session 3</td>
<td>M. Słowakiewicz (University of Bristol)</td>
<td>Biomarker Indicators of Bacterial Activity in the Upper Permian (Zechstein) Carbonate Microbialites and Facies from the Southern and Northern Permian Basins of Europe.</td>
</tr>
<tr>
<td>14.40</td>
<td></td>
<td>P. Wright (BG Group)</td>
<td>Microbial aragonite in a calcite sea: Carboniferous microbialite reservoir, Karachaganak Field, Kazakhstan.</td>
</tr>
<tr>
<td>15.05</td>
<td>Break</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15.35</td>
<td></td>
<td>Gareth Jones (ExxonMobil)</td>
<td>Spatial and Temporal Evolution of Burial Diagenesis Driven by Geothermal Convection in Pre-Salt Lacustrine Carbonate Reservoirs</td>
</tr>
<tr>
<td>16.00</td>
<td></td>
<td>M. Badali (Repsol Exploration)</td>
<td>Lower Cretaceous Marine Microbial Reef Classification, Distribution, and Porosity Trend in Northeastern Gulf of Mexico.</td>
</tr>
<tr>
<td>16.25</td>
<td></td>
<td>J. Buckley (CGG)</td>
<td>Carbonate Buildups in the Santos Basin, Offshore Brazil.</td>
</tr>
<tr>
<td>16.50</td>
<td></td>
<td>M.C. Muniz</td>
<td>FMI-based Facies Model and Stratigraphic Analysis of Aptian (Pre-Salt) Microbial Carbonates from the Southern Campos Basin, Brazil</td>
</tr>
<tr>
<td>17.15</td>
<td>Finish</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Thursday 20 June

<table>
<thead>
<tr>
<th>Time</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>08.30</td>
<td>Registration</td>
</tr>
<tr>
<td>09.15</td>
<td>Welcome</td>
</tr>
<tr>
<td>09.30</td>
<td><strong>Session Chairs: Dan Bosence and Mark Aurell</strong></td>
</tr>
<tr>
<td>09.30</td>
<td><strong>Keynote Speaker: G. Della Porta (University of Milan)</strong></td>
</tr>
<tr>
<td></td>
<td>Non Marine Carbonates: Variety and Porosity of Microbially Mediated and Abiotic Fabrics.</td>
</tr>
<tr>
<td>10.00</td>
<td><strong>Keynote Speaker: P. Wright (BG Group)</strong></td>
</tr>
<tr>
<td></td>
<td>To be or Not to be, Microbial: Does it Matter?</td>
</tr>
<tr>
<td>10.30</td>
<td><strong>M.F. de Rezende (Petrobras / Texas A&amp;M University)</strong></td>
</tr>
<tr>
<td></td>
<td>Importance of Microbial Texture for the Porosity Characterization in Microbial Carbonates.</td>
</tr>
<tr>
<td>10.55</td>
<td>Break</td>
</tr>
<tr>
<td>11.25</td>
<td><strong>I. Sharp (Statoil)</strong></td>
</tr>
<tr>
<td></td>
<td>Pre- and Post-Salt Non-Marine Carbonates of the Namibe Basin, Angola.</td>
</tr>
<tr>
<td>11.50</td>
<td><strong>N. Rameil (Maersk Oil)</strong></td>
</tr>
<tr>
<td></td>
<td>Lithocodium-Bacinella Build-Ups in the Lower Aptian of the SE Arabian Peninsula - Implications for Reservoir Geology.</td>
</tr>
<tr>
<td>12.15</td>
<td><strong>A. Bahniuk (Geological Institute ETHZ Switzerland)</strong></td>
</tr>
<tr>
<td></td>
<td>Microbialite Facies of Lower Cretaceous Codó Formation (Northeast Brazil): Coupled Sedimentological and Isotope Paleoenvironmental Analysis of a Potential Reservoir Rock.</td>
</tr>
<tr>
<td></td>
<td><strong>Session 4: Cenozoic Session Chairs: William Morgan and Giovanna Della Porta</strong></td>
</tr>
<tr>
<td>12.40</td>
<td><strong>A. Virgone (TOTAL)</strong></td>
</tr>
<tr>
<td></td>
<td>Continental carbonates reservoirs: the importance of analogues to understand presalt discoveries</td>
</tr>
<tr>
<td>13.05</td>
<td>Lunch and Posters</td>
</tr>
<tr>
<td>14.25</td>
<td><strong>P. Buchheim (Loma Linda University)</strong></td>
</tr>
<tr>
<td></td>
<td>Microbialites of the Eocene Green River Formation as Analogs to the South Atlantic Pre-Salt Carbonate Hydrocarbon Reservoirs.</td>
</tr>
<tr>
<td>14.50</td>
<td><strong>C.R. Miller (Chevron Energy Technology Company)</strong></td>
</tr>
<tr>
<td></td>
<td>Microbial Oolites: Rock But Not Necessarily Roll.</td>
</tr>
<tr>
<td>15.15</td>
<td><strong>R.L. Baskin (University of Utah)</strong></td>
</tr>
<tr>
<td></td>
<td>Controls on Lacustrine Microbialite Distribution in Great Salt Lake, Utah.</td>
</tr>
<tr>
<td>15.40</td>
<td>Break</td>
</tr>
<tr>
<td>16.10</td>
<td><strong>C.A. Scholz (Syracuse University)</strong></td>
</tr>
<tr>
<td></td>
<td>Lacustrine Carbonate Facies in Extensional Settings: Case Studies from Lakes in East Africa’s Great Rift Valley.</td>
</tr>
<tr>
<td>16.35</td>
<td><strong>P. Corbett (Heriot-Watt University, Edinburgh)</strong></td>
</tr>
<tr>
<td></td>
<td>Microbial Carbonates - A Sampling and Measurement Challenge for Petrophysics.</td>
</tr>
<tr>
<td>17.00</td>
<td><strong>S. Claes (KULeuven)</strong></td>
</tr>
<tr>
<td></td>
<td>3D Visualization and Quantification of the Porosity Network in Travertine Rocks.</td>
</tr>
<tr>
<td>17.25</td>
<td>Finish and Summing Up – William Morgan</td>
</tr>
</tbody>
</table>
### Posters - 19 and 20 June

<table>
<thead>
<tr>
<th>12:20</th>
<th>19th June - Posters Introduction in the Lecture Theatre</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>P. Homewood (Geosolutions TRD)</td>
</tr>
<tr>
<td></td>
<td>Microbial textures, facies and geobodies: outcrop analog with features ranging from mm-scale to 100m-scale in Precambrian-Cambrian carbonates, Qarn Alam, Oman.</td>
</tr>
<tr>
<td>2</td>
<td>J.E. Amthor (Petroleum Development Oman)</td>
</tr>
<tr>
<td></td>
<td>Facies and Reservoir Characterisation of a Terminal Neoproterozoic Carbonate Platform Margin Escarpment, South Oman Salt Basin.</td>
</tr>
<tr>
<td>3</td>
<td>E. Le Ber (Royal Holloway University of London)</td>
</tr>
<tr>
<td></td>
<td>Neoproterozoic microbialites in a frontier basin: the Rasthof Formation (Cryogenian), northern Namibia.</td>
</tr>
<tr>
<td>4</td>
<td>M. Aurell (University of Zaragoza)</td>
</tr>
<tr>
<td></td>
<td>Controls on microbial-sponge buildup development (Bajocian, NE Spain).</td>
</tr>
<tr>
<td>5</td>
<td>F.N. Sadooni (Qatar University)</td>
</tr>
<tr>
<td></td>
<td>Microbial-mediated dolomite from Abu Dhabi coastal sabkha sediments as analogue to the Mesozoic dolomite of the Arabian Plate.</td>
</tr>
<tr>
<td>6</td>
<td>T.C. Chidsey (Utah Geological Survey)</td>
</tr>
<tr>
<td></td>
<td>Modern and Ancient Microbial Carbonates in Utah, U.S.A.: Examples from Great Salt Lake and the Uinta Basin’s Tertiary (Eocene) Green River Formation.</td>
</tr>
<tr>
<td>7</td>
<td>M.D. Vanden Berg (Utah Geological Survey)</td>
</tr>
<tr>
<td>8</td>
<td>A. Bahniuk (Geological Institute ETHZ Switzerland)</td>
</tr>
<tr>
<td></td>
<td>Coupled molecular and 14C studies of microbial carbonate laminae formation and growth rates in modern dolomitic stromatolites from Lagoa Salgada, Brazil.</td>
</tr>
<tr>
<td>9</td>
<td>C. Arenas (University of Zaragoza)</td>
</tr>
<tr>
<td></td>
<td>Quaternary and modern continental microbial deposits in the Iberian Range (NE Spain): possible analogues of fluid reservoirs.</td>
</tr>
<tr>
<td>10</td>
<td>S.N. Tonietto (Petrobras / Texas A&amp;M University)</td>
</tr>
<tr>
<td></td>
<td>Correlation of Depositional Microbial Microfabric Texture, Diagenetic Events and Petrophysical Properties of Upper Jurassic Smackover Formation thrombolites.</td>
</tr>
<tr>
<td>11</td>
<td>S. Pla-Pueyo (Royal Holloway University of London)</td>
</tr>
<tr>
<td></td>
<td>Microbialites in Neogene-Quaternary Basins of the Betic Cordillera (Southern Spain): Potential Outcropping Analogues for Tufaceous Reservoirs</td>
</tr>
</tbody>
</table>
Oral Presentation Abstracts
(Presentation order)
Wednesday 19 June
Session One: Precambrian
Keynote Speaker: Microbialites in Time and Space

Stanley M. Awramik, Department of Earth Science, University of California, Santa Barbara, CA 93106 USA

Of all the fossils known from the geologic record, microbialites trump all others in terms of a combination of their antiquity, age range, size range, diversity of environments, mineral composition, and even complexity. They are forming today, which presents the opportunity to understand present-day processes and apply them to the fossil record. As a structure or deposit produced by microbial sediment trapping and binding, and/or mineral precipitation, they include most notably stromatolites, thrombolites, dendrolites, leiolites, microbial boundstones, microbially induced sedimentary structures (MISS), carbonate mounds, tufas, and travertines. In practice, the last two categories are usually treated separately from microbialites. The vast majority of microbialites are composed primarily of calcite and aragonite; however, there are numerous other minerals involved, but these are volumetrically small by comparison. The focus here is on carbonate microbialites.

Cyanobacteria are the driving force for the vast majority of microbialites today and presumably this was the case throughout most of geologic time. Cyanobacteria dominate the sediment-fluid interface forming what is commonly called a microbial mat (the external surface of the accreting microbialite). As such, they have the greatest influence on overall shape and probably microstructure. The cyanobacteria can actively trap and bind detrital sediment and their photosynthesis and EPS can result in carbonate precipitation. At microscale depth within a mat, other microbes are vertically zoned along chemical and light gradients. These microbes cycle organics and nutrients, they can precipitate (e.g., sulfate reducers) and dissolve calcium carbonate (e.g., sulfur oxidizers), and act on the ‘primary’ or initially accreted and precipitated sediment and modifies original microstructure, as well as original porosity and permeability. Although the vast majority of recent and ancient stromatolites grew in shallow water within the photic zone, there are examples of microbial carbonates (boundstones and giant mounds) that formed below the photic zone and hence are non-cyanobacterial in origin. These have unfortunately been out of mainstream microbialite studies.

I group microbialites into four, broad phases of development: (1) Archean (oldest at 3475 Ma through about 2500 Ma); (2) Proterozoic (2500 to 541 Ma), (3) Phanerozoic (younger than 541 Ma); and (4) present–day, actively forming microbialites. Phases 1-3 also have subthemes. It’s not surprising that these phases reflect eons of the geologic time scale. On a coarse scale, the cyanobacterial microbial communities building microbialites track the evolution of the Earth system. However, in one case, they and their planktonic brethren didn’t track, but changed the game: they brought about the radical transformation of redox conditions on the Earth starting with the Great Oxidation Event occurring about 2300 Ma. Today, phase 4, microbialites are most diverse with regard to depositional settings, forming in marine environments, lakes (even ice-covered), streams, springs, soils (caliche), caves, etc. The same is probably true for the past, but some environments have a low preservation potential and are difficult to recognize. Environments well represented in the Archean include near-shore, shallow-marine, lakes, and possibly hydrothermal vents. The Proterozoic includes the richest and most diverse record of marine microbialites known. Other settings include lacustrine and fluvial. Marine diversity drops in the Neoproterozoic and is low in the Phanerozoic. But the Phanerozoic still has abundant marine microbialites (not uniformly distributed with respect to geologic time) and these are usually coarser grained than their pre-Phanerozoic counterparts and hence had greater original porosity. The Phanerozoic has an excellent record of lacustrine stromatolites and among the many lacustrine formations known, the Eocene Green River Formation probably has the richest and most diverse array of microbialites, including large bioherms.

Large, multimeter-size bioherms or reefs are not a common megastructure for microbialites. Most are found comprising biostromes or isolated structures or clusters of microbialites a meter or less high or thick. In the marine realm, the sole reef builders in the pre-Phanerozoic were...
microbialites with some impressive dimensions. Individual bioherms over 200 m high and over a km wide are known from Mesoproterozoic and some Paleoproterozoic reef complexes and are a few tens-of-meters thick and occur along strike for hundreds of kilometers. For the Phanerozoic, microbialites accompany skeletal metazoans in reef-building in photic zone settings. However, chemosynthetic microbes below the photic zone can produce “giant” carbonate mounds a few hundred meters high and several kilometers long in present-day, deep marine settings. Similar giant mounds are also known from the Phanerozoic and possibly Proterozoic.

Lakes, the second most common setting for microbialites, do not have many large buildups or reefs. When found, they are commonly spring related such as the ones in present-day Lake Van (40 m high) and Pleistocene, Searles Lake (tufa mounds up to 45 m high). An exception may be the 30 m by 8 km microbialite bioherm in the Uinta Basin of the Eocene Green River Formation.

Microbialites represent complex microbial communities that have been operating continuously on the surface of the Earth for over 3400 million years. They proliferated in shallow marine settings early in the Archean, were well established in lacustrine systems by the late Archean, consumed CO$_2$ producing O$_2$ resulting in the oxygenation of Earth’s atmosphere, were widespread and diverse in the Proterozoic, persisted with great success in the Phanerozoic despite being subjected to animal interference, survived mass extinctions often thriving in their aftermath, and if all that isn’t enough, they even managed to produce and store hydrocarbons.
3D Digital Reservoir Model of a Microbialite Reef in the Neoproterozoic Nama Group in Namibia

Gerd Winterleitner¹, Bernie Vining¹,², Daniel Paul Le Heron¹, Rebecca Morgan³, Carlos Figueiredo⁴, Obeth Mbui Kandjoze⁵, Benjamin Mapani⁶

¹Department of Earth Sciences, Queen’s Building, Royal Holloway University of London, Egham, Surrey, TW20 0EX, UNITED KINGDOM.
²Baker Hughes, Bentley Hall, Alton, Hampshire, GU34 4PU, UNITED KINGDOM.
³Baker Hughes, Aldine Westfield Road, Houston, Texas 77073, USA.
⁴Sonangol P&P, Avenida 4 de Fevereiro no. 197, Luanda, ANGOLA.
⁵Namcor, 1 Aviation Road, Petroleum House, Private Bag 13196, Windhoek, NAMIBIA.
⁶University of Namibia, Faculty of Science, Department of Geology, Private Bag 13301, Windhoek, NAMIBIA.

In this study, we describe and interpret a reservoir analogue model constructed from a Neoproterozoic thrombolite-stromatolite reef system. Due to the increasing significance of these systems as possible hydrocarbon reservoirs, a better understanding of their internal structure is required.

A new frontier in approaching this problem is the development of digital outcrop models (DOMs). These are highly valued datasets in petroleum geoscience because they allow all elements of a petroleum system to be imaged in detail. Light detection and ranging (LiDAR) is a technique that has come to the forefront of creating DOMs in the last decade. This laser-based measurement system allows the rapid acquisition of detailed point data describing an outcrop in 3D with high precision of a few centimeters. In conjunction with traditional mapping methods, these 3D photorealistic DOMs are used for the development of static and dynamic reservoir models. Field geologists can bring the outcrop virtually to the office.

As a potential reservoir analogue, outcrops of the Omkyk Member in the Neoproterozoic Nama Basin of Namibia were chosen for the development of a DOM. The exceptional quality of the outcrops provides an excellent opportunity to study a microbial dominated reef system as a potential reservoir. This reef complex developed in a wave-dominated inner carbonate-ramp setting and it is characterized by the evolution of individual thrombolite-stromatolite build-ups. Previous studies have shown that the spatial distribution of the reefal build-ups is the major constraint on the reservoir quality and connectivity. However, these studies have not investigated the fracture and fault network, which has a major impact on the connectivity between the individual build-ups and consequently on the reservoir quality.

An area of approximately 3 km² was scanned and digitized and the contribution of the fracture patterns to the reservoir quality was evaluated. A geocellular reservoir model was developed with the modeling software JewelSuite™ to simulate the interplay between vertical and lateral facies changes and fracture sets.

In order to calibrate the geocellular model to the subsurface so-called pseudo-wells were constructed. The development of the pseudo-wells is based on data from the LiDAR survey and field mapping and additionally incorporates subsurface data such as image logs, wireline and LWD responses of microbial carbonates. These pseudo-wells are used to simulate various well trajectories to define the best practice for the exploration and development of these microbial carbonate reservoirs.

The static reservoir model will subsequently be used in a series of sensitivity tests for reservoir simulation. It is envisaged that this research will have direct exploration and production significance in optimizing the location and trajectory of wells, drilling, formation evaluation and completion practices.
In this paper, we demonstrate how LiDAR based mapping and the quantitative acquisition of fracture and fault patterns in conjunction with traditional field mapping methods improve our understanding of microbial carbonate reservoirs. Furthermore, we describe a methodology how to link a reservoir analogue model to the subsurface and show workflows how to upscale a high-resolution LiDAR dataset for using in static reservoir modeling. The geocellular reservoir model and the developed workflows can be used as a base model for microbialite reservoirs.

This study showcases the benefits of returning to the outcrop in better understanding of microbial carbonate reservoir heterogeneity.
Ara Group Reservoirs of the South Oman Salt Basin: Isolated Microbial-Dominated Carbonate Platforms in a Saline Giant

Joachim E. Amthor, Petroleum Development Oman, Muscat, PC 113, Sultanate of Oman

Isolated carbonate platforms, of terminal Neoproterozoic to earliest Cambrian age, form prolific reservoirs within the Ara Group intra-salt petroleum system of South Oman. The Oman salt basins formed (and were later deformed) during transtensional and transpressional tectonics within a compressional plate setting (i.e. the Pan-African amalgamation of Gondwana). The age of the Ara Group is well constrained by volcanic ash beds which have been dated using high-precision U-Pb geochronology. The available age dates and their extrapolation bracket the deposition of the Ara Group between ca. 548 to 537 Ma.

The Ara Group comprises at least seven third-order evaporite/carbonate depositional sequences, some of which contain prolific hydrocarbon reservoirs. Each sequence contains several isolated carbonate platforms, with reservoirs developed according to primary facies distributions.

The main reservoirs occur in dolomitised, approximately 100 m thick, isolated carbonate platforms (known as ‘Ara Carbonate Stringers’), which are fully encased in evaporites (mainly anhydrite and halite) that provide base and top seals. The Ara platforms formed during transgressive to highstand accommodation conditions, superimposed upon a progressive, long-term accommodation increase that forced platforms within each sequence to occupy progressively less area. Older platforms are thinner and laterally more extensive, intermediate age platforms are thicker and more differentiated with respect to shelf margin and slope-to-basin facies, younger platforms are thinner again, often dominated by deeper-water facies, and the youngest consist of numerous small pinnacle reefs. Platform facies include microbial boundstones, intraclast-peloid-ooid grainstone-packstone, and mudstone. Microbial facies dominate, and display a variety of textures that conform to systematic variations in water depth and inferred accommodation regime. Platform interior facies consist of peritidal stratiform stromatolites with pustular, smooth, and tufted textures. These pass laterally into thrombolite sheet and mound facies, which pass downslope into turbiditic mudstones that interfinger with crinkly laminites in the most distal settings. Crinkly laminites are widespread in basinal settings and result from accumulation of both pelagic and benthic microbial organics. These basinal microbialites form one reservoir type whose performance deteriorates in proportion to the influx of turbiditic shelf-derived muds. Other reservoirs are developed principally in shelf interior to shelf margin microbialites and associated grainstones. Reservoir quality in microbialites reflects the primary (inefficient) growth fabric of thrombolites, and the early diagenetic decay of microbial mats in more stromatolitic facies.

The bulk of the hydrocarbons within the stringers is derived from intra-salt source rocks, deposited as sapropelic laminites and laminated mudstones in basinal settings.

A recent oil discovery in a > 400m thick sequence of Ara carbonates without intervening evaporites has highlighted the range of stratigraphic play types and lateral facies variations to be encountered in the Ara Salt Basins.

Seismic data show the stacked sequence as a prominent transparent package that thins westward. Towards the east, the package is characterised by a steep transition into the deeper basin. This prominent carbonate escarpment strikes NE/SW, following the underlying basement trends, and is dissected by NW/SW trending faults which play an important sealing role. The available well and core data reveal depositional facies that indicate the presence of a highly productive microbial boundstone factory.

Characteristic facies include a variety of stromatolite and thrombolite boundstones and associated grainstones, oolitic and intraclast pack/grainstones, calcrite and pisod-dominated...
facies with tepee structures. In particular, isopachous stromatolites and pisolitic units are indicator facies, which have not been observed to date in typical Ara Carbonate Stringer reservoirs. Diagenetic elements that are present and which have altered and/or obliterated the depositional facies are: pervasive dolomitisation, evidence for multiple episodes of dissolution and brecciation during periods of subaerial exposure, isopachous and fibrous early diagenetic (marine) cementation and fault-related dissolution and cementation. The depositional and early diagenetic matrix complexities are compounded by fault and fracture related processes that have generated locally enhanced matrix permeability.

The Ara reservoirs of the South Oman Salt Basin are characterized by high degrees of reservoir heterogeneity at the core plug, well and inter-well scales. Plug data exhibit Dykstra-Parsons coefficients in the range 0.85 to 0.97. Vertical inflow profiles constructed from plug and PLT data indicate that in many cases, as little as 10-20 percent of the reservoir thickness actually contributes fluid flow into the well. Large variations in well test KH and Productivity Index are observed between adjacent wells. These variations in permeability are the result of the complex interplay of a range of diagenetic and depositional processes. High permeabilities are particularly associated with dolomitised, vuggy microbial facies (e.g thrombolites). Tight intervals are variously associated with non-microbial depofacies, calcite cementation, the emplacement of reservoir bitumen and salt/anhydrite plugging.

To this date, the identification and interpretation of Precambrian-specific lithofacies and depositional environments and their translation into (predictive) exploration play models and production-scale reservoir models remains a major challenge. The appraisal drilling has highlighted the potential and the challenges for reservoir of the platform margin escarpment. Particular uncertainties still exist in terms of detailed reservoir architecture, aquifer development and prediction of permeability and modelling the dynamic flow behaviour and fluid displacement / sweep in these heterogeneous carbonates.
Reservoir Quality in the A2C-Stringer Interval of the Late Neoproterozoic Ara-Group of the South Oman Salt Basin: Diagenetic Relationships in Space and Time

Stephan Becker¹, Lars Reuning², Peter A. Kukla², Steffen Abe³, Shiyuan Li³, Janos L. Urai³, Suleiman Farqani⁴, Gideon Lopes Cardozo⁴, Zuwena Rawahi⁴

¹LuFG Reservoir Petrology (RWTH Aachen University), former Geological Institute (RWTH Aachen University)
²Geological Institute (RWTH Aachen University)
³Structural Geology, Tectonics and Geomechanics (RWTH Aachen University)
⁴Petroleum Development Oman

The Ediacaran-Early Cambrian Ara Group of the South Oman Salt Basin consists of six (microbial) carbonate to evaporite (rock salt, gypsum) sequences. These Ara Group carbonates are termed A0C to A6C from the bottom towards the top of the basin. Differential loading of locally 5 km thick Cambrian to Ordovician clastics onto the mobile rock salt of the Ara Group caused growth of isolated salt diapirs, which resulted in strong fragmentation and faulting of the carbonate intervals into several isolated so-called ‘stringers’. These carbonate stringers represent a unique intra-salt petroleum system, which has been successfully explored in recent years. However, some of the stringers failed to produce at significant rates due to the complex diagenetic history from the shallow to the deep burial realm.

The goal of this study is twofold. Firstly, to unravel the complex diagenesis and its relative timing and link them to the burial history of the salt basin. Secondly, to detect spatial distribution patterns of diagenetic phases and their effect on reservoir properties. Mineralogy, rock fabrics, paragenetic relationships and geochemistry of ~ 400 samples from several petroleum wells from the late Neoproterozoic A2C interval were analyzed and combined with pre-existing data. The spatial distribution of diagenetic phases and petrophysical characteristics will be displayed in field-scale distribution maps. These maps comprise crucial information for better prediction of reservoir quality in the analyzed fields, planning of new exploration wells and better volumetric calculations.

An integration of the paragenetic sequence derived from thin-section analysis with results from finite element and discrete element models further helps to constrain the effect of salt tectonics on fracture formation and fluid evolution within the stringers.
Preservation of Microbial Textures and Primary Depositional Features in Precambrian-Cambrian Carbonates, Qarn Alam, Oman

Monique Mettraux¹, Marcelle Erthal², Peter Homewood¹, Said Al Balushi³, John Grotzinger⁴, Nilo Matsuda⁵

¹GEOSOLUTIONS TRD c/o Petrobras E&P, Rio de Janeiro, Brazil
²CENPES, Petrobras, Rio de Janeiro, Brazil
³PDO, Muscat, Oman
⁴Caltech, Pasadena, USA
⁵Petrobras E&P, Rio de Janeiro, Brazil

Late Proterozoic to Early Palaeozoic microbial carbonate rocks are exposed by surface-piercing salt domes in central Oman. The Qarn Alam salt dome outcrops comprise numerous blocks of microbial facies that are organised in laterally extensive, 10m-scale laminite-stromatolite-thrombolite shallowing-up and emersive cycles. The facies, the geometrical relationships and fine scale textures on the outcrops, from scales of tens of metres down to millimetres, strongly suggest the preservation of original depositional textures. These facies are thought to be analogs of the South Oman Salt Basin “Stringer” reservoirs.

A broad range of analytical and laboratory studies unequivocally confirm the synsedimentary and syndepositional diagenetic nature of these microbial carbonates. Despite the ≈540-550Ma age of the microbialites, in addition to the more rare occurrence of both coccoid and filamentous or other microbial forms, the mineralisation of the structure of the original alveolar EPS matrix entirely matches that of dolomite and calcite in modern microbial mats from the Abu Dhabi sabkhas or from Eleuthera, Bahamas (as shown by SEM images of highly porous and finely crystalline dolomite of the thrombolite facies, Figure 1).

Laminite and stromatolite facies are composed of irregular, simple or “tufted mat” layers, comprising mm-size clots and larger clumps of clots that are both imaged by fluorescence microscopy and seen as micritic peloids under the light microscope. The little organic matter that is preserved is composed of laminated amorphous material.

Stromatolite and thrombolite facies reveal a complex progression of initial and subsequent steps, many of them syndepositional, which must have been repeated lamina by lamina to layer by layer during sedimentation. The sequence of events was deduced by light microscopy and cathodoluminescence petrography studies. Thrombolite mesoclots are either composed of layered clumps of clots (“layered thrombolite”) or are bushy, branching structures of a precursor form (“bushy thrombolite”) that has been replaced during sedimentation by an infill comprising both clots and aragonite needle clusters. The finely crystalline dolomite matrix was deposited either as a mass between and around the bushy mesoclots, or as layers between layers of mesoclots, as well as enveloping clumps of clots. This matrix is the result of the mineralisation of an alveolar structure that is directly comparable with microbial EPS.

The growth and mineralisation of the matrix took place layer by layer for the layered thrombolite, whereas the more massive matrix of the bushy thrombolite may have developed following the growth of a bushy precursor form (perhaps a sponge?). But this growth certainly took place before, or together with, the degradation of the precursor and the infill of the empty cavities that mold the precursor shape.

The strong variation of δ¹⁸O within thrombolite laminae and between discrete mineral phases in a same lamina, as well as the repeated pattern of variation in successive stratigraphic layers of a laminite-stromatolite-thrombolite shallowing up sequence, show that little resetting of stable isotope values has taken place. Consistent values of +4δ¹³C and +/-0δ¹⁸O suggest slightly heavier δ¹⁸O values for carbonates in equilibrium with late Proterozoic seawater than previously has been reported.
In the bushy thrombolites, a brightly luminescent phase of calcite replaces aragonite needle clusters, and cements hairline fractures that cut across the mesoclots and matrix. This records a step when the sediment was slightly lithified ("crumbly") and lightly leached, but after which further cementation by calcite, as well as more fracturing, indicate a progressively more indurate rock. The optical continuity of fascicular calcite crystals, from the thrombolite mesoclots, across early cement phases to later burial cement, indicates a minor degree of recrystallisation starting at an early, prelithification stage. However, the limited negative shift of δ\(^{18}\)O values in calcite of mesoclots, compared to the values of the finely crystalline dolomite of the matrix, precludes any major resetting of stable isotope values and therefore indicates no major diagenetic changes.

Later burial diagenesis took place with growth of non-luminescent calcite cement in optical continuity with earlier cements. This phase fills later fractures and partially occludes vuggy pore space. These later cements are characterised by much lighter values of both δ\(^{13}\)C (-2 to -6‰) and δ\(^{18}\)O (-8 to -11‰). No components show stable isotope values that are intermediate between the later phases and the earlier, syndepositional phases. A considerable amount of the primary texture, mineralogy, pore space and pore network has apparently been preserved.

No isotopic values of -4δ\(^{13}\)C indicating the Precambrian-Cambrian boundary have been measured. So it is plausible that the Qarn Alam microbialites are coeval either with the Terminal Proterozoic A3C or with the Earliest Cambrian A5C Ara Formation carbonate units in the subsurface of the South Oman Salt basin.

Figure 1: Comparison of microbialite textures between Qarn Alam (left) and Abu Dhabi (right). Note highly comparable 2µm -10µm scale alveolar structures.
Wednesday 19 June
Session Two: Palaeozoic
Biomarker Indicators of Bacterial Activity in the Upper Permian (Zechstein) Carbonate Microbialites and Facies from the Southern and Northern Permian Basins of Europe

Mirosław Słowakiewicz$^{1,2}$, Richard D. Pancost$^1$, Maurice E. Tucker$^{3,4}$, Mike Mawson$^4$, Edoardo Perri$^5$

$^1$Organic Geochemistry Unit, Bristol Biogeochemistry Research Centre and Cabot Institute, School of Chemistry, University of Bristol, Cantock’s Close, Bristol BS8 1TS, UK
$^2$Polish Geological Institute, Polish Geological Survey, ul. Rakowiecka 4, 00-975 Warsaw, Poland
$^3$Department of Earth Sciences, University of Bristol, Bristol BS8 1RJ, UK
$^4$Department of Earth Sciences, Durham University, Durham DH1 3LE, UK
$^5$Dipartimento di Scienze della Terra, Universita della Calabria, Rende, Italy

One of the most important hydrocarbon-bearing palaeobasins in Europe is the evaporite-carbonate Southern (SPB) and Northern (NPB) Permian Basin and especially their most petrolierous second carbonate unit (Z2C, also referred as the Main Dolomite, Roker Fm. or Staβfurt Karbonat, ca. 254 Ma) of the second Zechstein (Lopingian) cycle. Although extensively studied, there is still a lack of sufficient data on the extensive microbial facies in the Z2C which are the reservoir rocks, and probably the source rocks too for the hydrocarbons.

Existing geochemical proxies such as scarce biomarkers, major and minor elements, sulphur and strontium isotopes do not provide sufficient information about the type of organic matter and sedimentary conditions in the Z2C sea. In order to circumvent this problem a biomarker-based approach was used on 100 samples from 15 boreholes and outcrops to characterize the biomarker distribution in the various Z2C depositional zones containing significant amounts of microbialite (stromatolites and thrombolites) from the northern and western and southern margin of the SPB, namely lagoonal, ooid shoal, slope, toe-of-slope apron and basinal facies. Sedimentologically, the lagoonal facies are characterized by dolomitized microbial boundstone and packstone (interfingering with evaporites (anhydrite), especially in NW Poland). Ooid shoal facies are built of dolomitized ooid grainstone; slope facies are largely represented by dolomitized or dedolomitized biolaminitic mudstone and turbidite packstones, microbial boundstone, floatstone and rudstone, and toe-of-slope apron facies consist of dolomitized interbedded units of oolitic packstone, carbonate conglomerates and debrites with microbialite fragments. Basinal facies are represented by very thin laminated clayey calcareous mudstones.

The most diagnostic and useful signatures of Z2C organic matter in slope, toe-of-slope apron and lagoonal facies are the occurrence of 1) 2,3,6-aryl isoprenoids (C$_{15}$ to C$_{31}$), isorenieratane and β-isorenieratane derived from brown-pigmented green sulphur bacteria, 2) rare chlorobactane characteristic of green-pigmented green sulphur bacteria, 3) C$_{31}$ and C$_{32}$ 2αβ-methylhopanes (only found in dedolomitized outcropping Z2C slope facies), essentially characteristic of cyanobacteria, and 4) a low sterane/hopane ratio (<0.2) suggesting microbial or microbially reworked organic matter. In addition, the occurrence of aryl isoprenoids (likely degradation products of isorenieratane), isorenieratane, β-isorenieratane and chlorobactane indicates that part of the photic zone, limited to the toe-of-slope apron, slope and lagoonal depositional zones, had become euxinic. Basinal facies are in general significantly depleted or lacking steranes, hopanes and polycyclic aromatic hydrocarbons, and largely contain terrestrial-type organic matter. Ooid shoal facies contain hopanes, low concentrations of steranes, a lack of aromatic carotenoids and benzo hopanes.

The thermal maturity, assessed from Ts/(Ts+Tm), C$_{30}$ moretane/hopane, 20S/(20S+20R) and ββ/(ββ+αα) steranes, shows a mature character of the organic matter with respect to oil generation. The marginal parts of the basin and hypersaline lagoons during Z2C deposition were dominated by the activity of green sulphur bacteria which possibly coexisted with sulphate reducing bacteria, as suggested by the occurrence of very low amounts of native sulphur and microcrystals of pyrite. It also seems that cyanobacteria played an important role in carbon cycling and burial diagenesis, as suggested by the presence of specific biomarkers in the dedolomitized outcropping slope facies. Euxinic conditions may additionally have promoted
microbial productivity and preservation, with only a low contribution of terrestrial and algal (phytoplankton) organic matter.
Characterization of the Microbial-Dominated Slopes of Super Giant Tengiz and Korolev Oil Fields, Pricaspian Basin, Kazakhstan

Steve Jenkins, Paul (Mitch) Harris, Eldar Iskakov, Steve Bachtel, Henry Posamentier, Miriam Andres, Ted Playton, David Katz, Frank Harris and Eric Flodin

1TengizChevron - TCO, Atyrau Oblast, Republic of Kazakhstan
2Chevron Energy Technology Company, San Ramon, California, U.S.A.
3Chevron Energy Technology Company, Houston, Texas, U.S.A.

High-fold and wide-azimuth 3D seismic data was recently acquired and processed over Tengiz and Korolev Fields, leading to improved reservoir characterization of the microbial-dominated fractured reservoirs. Variation in margin-slope characteristics has implications for modeling of reservoir quality, fracture distribution, and subsequent oil field development strategies. High amplitude seismic events (referred to as “mega-amplitude” events) are observed in the 3D seismic in the microbially dominated slopes of Tengiz Field (Jenkins, et al, 2012). These mega-amplitude events may result from solution enhancement of fractures via deep-burial corrosive diagenesis, resulting in high permeability fairways. These seismic events correlate with evidence for cavernous porosity in wells including lost circulation, bit drops, open calipers, and cavernous zones on image logs. Identification of cavernous porosity is important for understanding field performance and targeting high-rate wells. These observed mega-amplitude seismic events have been confirmed by seismic models of caverns and solution enhanced fracture fairways in the microbial boundstone.

Tengiz Field (15 x 15 km) is an isolated Paleozoic carbonate build-up containing approximately 26 billion bbls of oil in place. Tengiz is one of the world’s deepest supergiant fields and has a complex depositional and diagenetic history. Fracture dominated reservoirs characterize the microbial slopes; while matrix dominated reservoirs characterize the platform interior. The reservoir architecture has been described in detail by Weber et al (2003), Kenter et al (2006), Collins et al (2006). Platform backstepping through the Late Visean resulted in approximately 800 m of relief above a Famennian platform, followed in the late Visean to Serpukhovian by up to 2 km of progradation of a microbially-dominated margin and slope. Microbial-dominated and well-cemented boundstone slopes form one of the dominant reservoir facies, primarily due to localized fracturing and dissolution in the upper to middle slope. Margin/slope facies are identified from seismic characterization, core analysis, and wireline logs (primarily FMI logs). These facies include (from distal to proximal slope environments) platform-derived grainstone, coarse skeletal rudstone with boundstone clasts, massive boundstone breccia, and in-situ microbial boundstone ranging from upper slope to outer platform settings. The spatial distribution and proportions of facies are inferred from well and seismic data and outcrop analog concepts (Kenter et al, 2006) and can be viewed as occurring in accretionary and allochthonous sectors at Tengiz. Accretionary sectors are characterized by a conspicuous raised rim crest and a considerably wider progradational wedge, whereas the allochthonous sectors have a lower, distally thickened apron. Periodic rim failure during both Serpukhovian and Bashkirian time resulted in a high degree of lateral facies discontinuity within the slope. New Tengiz seismic data show that distinct processes were active in different margin sectors of the platform (Bachtel et al, 2012). Smaller-scale gullied slopes (100m in width) and larger-scale mass gravitational failure surfaces (kilometer scale) are observed in the high resolution seismic data.

Tengiz cores and FMI logs suggest that the in-situ microbial boundstone interval is perhaps 150–200 m thick. In-situ microbial boundstones are light colored in core, with textures that include relatively featureless micritic to peloidal fabrics or irregular laminar fabrics and amalgamated semiconcentric laminar masses. A third boundstone type, characterized by massive to peloidal fabric with common skeletal grains, represents the transition between upper-slope and outer-platform facies. Tengiz microbial boundstone samples contain very typical nanoglobules and grainy textures evidencing a distinctive microbial origin (Andres et al, 2012). Breccias are found in the Tengiz middle to upper slope. Clast size and packing varies in
the breccias, with textures ranging from matrix-supported float breccia to welded breccia with stylolite-bounded clasts. Clasts, from less than 1 cm to several meters in size, are dominantly upper-slope microbial boundstone fragments, although platform-derived clasts and reworked slope clasts are increasingly observed in breccias near the base of the section. Matrix consists mainly of several generations of calcite cement, secondary microbial encrustations, microbial cement, and minor amounts of platform-derived skeletal sediment, thin-bedded marly volcanics, or argillaceous carbonate.

Korolev Field (4 x 2 km) is a smaller isolated platform located 12 km NE of Tengiz Field. Microbial deposits at Korolev Field share some significant similarities and critical differences with those at Tengiz Field. Recent studies at Korolev have shown dominantly deeper water deposition for much of the life of the field. Microbial boundstone deposits at Tengiz are dominantly Serpukhovian age and are most common in the middle to upper slope environment. At Korolev, abundant microbial boundstone occurs from late Visean through Serpukhovian, and Visean boundstone deposits are interpreted across the entire platform based on FMI calibrated with seismic and limited core data. These differences in microbial boundstone distribution and diagenesis at Tengiz and Korolev Fields have contributed to the widely varying connectivity and well performance observed in these fields. At Tengiz, high rate wells are confined to the margin and upper slope locations where fractures are common in microbial boundstone. At Korolev, highly connected wells are observed in both margin and slope as well as platform top environments where microbial boundstone is widely distributed.

Paleozoic high-relief platforms with microbial boundstone-dominated margins and slopes, like Tengiz, Korolev, and similar reservoirs throughout the Pricaspian Basin, seem to have developed in mesotrophic, starved restricted basins with oxygen-depleted bottom waters that would not be suitable settings for recent coral-reef rimmed platforms. Our studies of the Tengiz high-relief margin and slope (Kenter et al, 2005, 2006, 2012; Collins et al, 2006; Andres et al, 2012; Bachtel et al, 2012) suggest several factors that broaden a perspective of microbial carbonates: 1) microbial-boundstone production extends to 300m water depth, 2) the detrital lower slope consists mostly of matrix-free cemented rudstone sourced by the slope boundstone with subordinate platform top derived material, 3) carbonate production on the slope is controlled by environmental parameters (temperature, nutrients, oxygenation), that may be directly or indirectly related to water depth, but the microbial boundstone response to relative sea-level changes differs from modern reefs, 4) carbonate growth is not seriously reduced during sea-level falls because it can continue downslope, 5) progradation can take place at high rates despite the lack of platform top shedding (slope vs. highstand shedding), 6) concepts of leeward progradational vs. windward aggradational margins do not directly apply, and 7) the exquisite preservation of microbial microtextures suggests early, if not instantaneous mineralization and thus stabilization of the slope environment and lack of later destructive re-mineralization.
Microbial Aragonite in a Calcite Sea: Carboniferous Microbialite Reservoir, Karachaganak Field, Kazakhstan

Paul Wright¹, Ornella Borromeo², Francesco Bigoni², Simon Beavington-Penney¹

¹BG Group, Reading, UK
²ENI, Milan, Italy

Mississippian microbial mounds are typically calcitic with low matrix porosities, reflecting their growth in calcite seas. The super-giant Karachaganak oil and gas field from Kazakhstan contains a range of late Devonian to early Permian carbonates but extensive oil reserves are hosted in mid Visean to late Serpukhovian mounded and slope facies with a prominent microbial component displaying evidence of a former aragonitic composition. Mound-dominated successions have thicknesses of over several hundred metres and a range of facies have been identified including bryozoan, cementstone and palaeoberesellid mounds. The distinctive microbial cementstones formed depositionally at an intermediate position between the deeper bryozoan mounds and shallower palaeoberesellid mounds.

The bryozoan-rich microbial mound complexes have typical thicknesses of 50-60m, based on well logs responses but in core are on average only a few metres thick, with estimated lateral extents of a few hundred metres. They are more frequent in the Late Visean section, and are characterised by a highly heterogeneous distribution of depositional facies. Their distribution may reflect antecedent topography related to syn-Mississippian tectonics.

The palaeoberesellid mounds are generally thinner, based on log response and occur near the margins of the platform in the Serpukhovian section.

Cementstone mound complexes potentially reach thicknesses of 100m based on log signatures, likely representing amalgamated units. Continuous cementstone intervals in cores are less than 10m thick. They are especially widespread in the Serpukhovian interval, both as large aggradational bodies and as prograding slope complexes. These cementstones consist of mm-scale botryoids, now calcite, with castellated margins, coated by sub-mm dense micritic to peloidal laminae. The strongly stromatolitic macro-structure and the fact that classical aragonite cements have not been found in cavities of this age in the field, suggests that the growth of the cementstones probably required light, supporting a possible phototrophic microbial origin. There is no evidence to support their production beneath phylloid algae. The age of these cementstones is pre-Bashkirian and so formed in a global calcite sea. This is supported by the fact that rare ooids from the late Serpukhovian platform interior were originally calcitic. This suggests that at the intermediate depths at which the cementstones formed, some local factor such as high alkalinity may have been over-riding normal calcite precipitation.

The microbial cementstones produce the best reservoir quality of the three mound types, and aragonite dissolution took place during shallow burial producing an extensive pore network, partly occluded by calcite cements. This pore network provided flow pathways for dolomitizing fluids, further enhancing porosity and permeability. Microbial cementstones were reworked as slope facies which also have reservoir quality. The Mississippian mound reservoirs in North America (Dickinson Field, N. Dakota; Bowar Field, Teaxas; Pekisko, Alberta), were calcitic with negligible matrix-porosity.

Classical Waulsortian mounds developed typically on ocean-facing carbonate ramps, whereas the Karachaganak mounds formed in a complex basin, where local geochemical conditions produced sea floor conditions favouring diagenetically labile mineralogies, and hence secondary porosity development. Their growth on local structural highs likely favoured upwelling and enhanced nutrient levels, and positioned them in part in waters capable of precipitating huge quantities of sea-floor aragonite, triggered by microbial activity.
Wednesday 19 June
Session Three: Mesozoic
Spatial and Temporal Evolution of Burial Diagenesis Driven by Geothermal Convection in Pre-Salt Lacustrine Carbonate Reservoirs

Gareth D. Jones, Yitian Xiao, ExxonMobil Exploration Company

Prolific deepwater hydrocarbon discoveries in the pre-salt section of the Santos Basin have created a business imperative to predict lacustrine carbonate reservoir quality. Dissolution related to exposure would likely have occurred in lacustrine carbonates subject to climatically driven changes in lake level as evidenced by seismic scale unconformities. In contrast, the potential to enhance reservoir quality by dissolution in the burial environment is poorly understood. Geothermal convection is a style of groundwater flow, driven by temperature induced variations in fluid density, capable of diagenetically modifying reservoir quality. Based on a Santos Basin half-graben conceptual model, we used Reactive Transport Models to evaluate the potential for diagenesis driven by convection. Specifically we tested the effect of variations in basal heat flux, lake temperature, permeability, faults, stratigraphic architecture (thickness and geometry), salt thickness, salt rugosity, salt minerals and pore fluid composition. Diagenetic rates are critically controlled by temperature gradient and fluid flux following the principles of retrograde solubility. Simulations predict that convection operates in lacustrine carbonates, prior to salt deposition but rates of dissolution in the reservoir interval are generally low being on the order of $10^{-2}$ to $10^{-4}$ volume % / M.y., and thus insignificant with respect to net diagenesis. The exception is around vertical faults where dissolution rates are amplified to $1 - 10$ volume % / M.y to locally enhance vertical connectivity. Post-burial simulations demonstrate the critical role of salt rugosity and the presence of salt withdrawal basins. The greatest potential for dissolution at rates of $0.1 - 1$ volume % / M.y occurs where salt welds thin to less than 300 m. Dissolution is greatest beneath the edge of the withdrawal basin in the top of the reservoir. With 10’s of M.y. available residence time, when the above conditions are satisfied, convection could locally result in porosity changes of 1-10 % and potentially an order of magnitude or more in reservoir permeability. By integrating our model driven predictive diagenetic concepts for geothermal convection and other diagenetic processes with traditional subsurface datasets we are able to further refine our exploration to production scale understanding and hypotheses of lacustrine reservoir presence and quality in the Santos Basin and elsewhere.
Lower Cretaceous Marine Microbial Reef Classification, Distribution, and Porosity Trend in Northeastern Gulf of Mexico

Marcello Badali, Repsol Exploration, Madrid, Spain

Up to the recent past the role of microbialites in Phanerozoic marine reefs has been underappreciated. In particular, classifications and paleoenvironmental reconstructions of marine Cretaceous microbialites are quite scarce. A few years ago microbial organisms have been discovered to play an important role in carbonate deposition in different geologic times. Furthermore, in the last years, a great focus has been placed on lacustrine carbonates, since they resulted to be a major hydrocarbon play in pre-salt Cretaceous deposits in Atlantic passive margins. Nevertheless, it should be considered that marine microbial reefs show also, in many cases, high quality reservoir characteristics and can be excellent producers (e.g. Tangiz field, Kazakhstan).

This work, representing a part of the author’s Ph.D. dissertation research which has not yet been published, focuses on the analysis of 527 meters of core from the Lower Cretaceous (LK) section of Mississippi, western Louisiana, and Alabama. Offshore data were placed in the sequence stratigraphic and lithostratigraphic framework established previously by the author through the interpretation of about 6000 km of 2D seismic lines and then correlated to the onshore data through the analysis of gamma ray and resistivity well logs.

The main goals of this part of the research were a new classification, based on micro and meso structure, of LK microbial constructors and the reconstruction of the depositional paleoenvironments of the microbial reefs cored in these wells. Also, an estimation of porosity values in the various microbial facies was performed (fig. 2).
Microbial structures (fig. 3) were divided in peloidal, alveolar, laminated, micritic massive, and micritic irregular microstructures and oncolitic, patchy, micritic massive, and laminated mesostructures. The alveolar microstructure is associated with the problematic alga *Bacinella irregularis/Lithocodium aggregatum*. The peloidal microstructure was produced by cyanobacteria. The remaining microstructures are associated with undifferentiated bacteria. *Pseudolithothamnium album* commonly occurs in association with any type of microbial boundstone.

Microbial boundstone occurs in most of the depositional settings investigated, primarily high-energy and secondly low-energy environments, such as middle-shelf, back-reef, shelf-edge, and slope settings (fig. 3). Also, these organisms contributed significantly to stabilize rudist and coral build-ups in high-energy shelf environments.

**Figure 3:** Depositional setting reconstruction and classification from this work of Lower Cretaceous microbial deposits in the study area. MS: mesostructure, ms: microstructure

In the study area shelf-edge lithofacies are represented by rudist and microbial boundstones in the southeastern part of the study area (Main Pass area) and by bioclastic banks and microbial boundstones in the northwestern part of the study area (Chandeleur area and Hancock County).

Most of the microbial deposits are associated with calcitic cement, which fills up most of the pores, however some of the middle-shelf and shelf-margin microbial deposits are characterized by fair-to-high interparticle and intraparticle porosity caused by the dolomitization of the cement. In recrystallized carbonates, microbial features often form relic structures.

In the few cases the cored wells were projectable on a seismic section, a chaotic internal seismic pattern and external mound geometry was observed in correspondence with high microbial facies occurrence (fig. 4).

**Figure 4:** Example of seismic-well-core integration in the Main Pass area. Eight depositional sequences (S1 to S8) were recognized. Microbial boundstone is here associated with chaotic seismic pattern and mound geometry
Carbonate Buildups in the Santos Basin, Offshore Brazil

J. P. Buckley¹, C. Elders², J. Mann¹

¹CGGVeritas, Crompton Way, Crawley RH10 9QN, UK
²Department of Geology, Royal Holloway, University of London, Egham, Surrey, TW20 0EX, UK

Interest in the Santos Basin initially surged in light of comparisons with the prolific Campos Basin to the north, which is responsible for over 80% of daily hydrocarbon production in Brazil. Global attention has more recently increased in the Santos Basin as a result of major discoveries in the pre-salt section. The first of these, the Lula field, is said to contain an estimated 6.5 bboe within a reported microbialite reservoir.

The Santos Basin combines several components to create an attractive pre-salt play; a thick & regionally extensive evaporite seal, a multitude of structural & stratigraphic traps and extensive topographic highs focusing charge migration. The hydrocarbons in the basin are sourced from syn-rift lacustrine shales contemporaneous with the world-class Lagoa Feia source rock of the Campos Basin. The key exploration uncertainty relates to reservoir distribution.

The Santos Basin is an extensional basin that formed as a result of the continental break-up of Western Gondwana, with rifting prevalent from the Neocomian until the late Aptian. As rifting ceased, drift tectonics became dominant in association with seafloor spreading in the Mid-Atlantic. The carbonate reservoirs of the Lula field were formed during the post-rift thermal subsidence phase, and thus the understanding of this so-called ‘sag sequence’ is key to reservoir prediction.

The pre-salt section has been extensively imaged with high quality 3D PSDM seismic data acquired by CGGVeritas, with the survey covering an area of over 41,000km² (Fig. 1). The dataset covers the extent of the Sugar Loaf & Tupi Highs, which form part of the Santos Outer High. The Tupi High is the structure in which the Lula field is located, with the Sapinhoa field and several other discoveries found on the Sugar Loaf High. This study is focused on the eastern margin of the Sugar Loaf High (Fig. 2).

The distribution of sedimentary facies across the high is controlled by the rift-generated topography created during continental break-up. Sedimentation occurred in a clastic starved environment due to the distal location of the basin, resulting in a predominantly carbonate succession. However, exposure of the basement in the most southerly part of the Sugar Loaf High means that in addition to the widespread precipitation of carbonates, there is also potential for the deposition of clastic lithologies.

The main pre-salt reservoir interval of the Santos Basin is comprised of what is thought to be a thick microbialite sequence with intermittent coquina beds, deposited during the sag phase. The sag carbonates of the Lula field are well-researched within the industry, whereas the carbonate buildups found on the margin of the Santos Outer High are less well known and understood (Fig 2 & 3). The features of interest are formed on an escarpment created by syndepositional faulting, resulting in a belt of carbonate buildups along the footwall margin.

The distinctive ‘serrated’ morphology of the buildups may relate to either erosional processes removing material downslope, thus creating an uneven margin topography, or depositional style. Strike sections through the margin suggest that these features are buildups as opposed to erosional features. The style of deposition may be analogous to the travertines of Pyramid Lake, or alternatively may represent a series of microbial mounds. An integrated approach using 3D seismic interpretation, palaeodepositional reconstruction & modern analogues will be used in determining the nature and genesis of these carbonate deposits.
Above: Fig. 1: CGGVeritas Survey location
Left: Fig. 2: Base Evaporite horizon, in which the carbonates can be seen as buildups along a horst margin

Right: Fig. 3: Aggradational morphology of carbonate buildups shown on a strike line
FMI-Based Facies Model and Stratigraphic Analysis of Aptian (Pre-Salt) Microbial Carbonates from the Southern Campos Basin, Brazil

Moises C. Muniz, Dan Bosence, Royal Holloway

A facies model and cycle-stratigraphy for the Aptian non-marine pre-salt microbialite carbonates (Macabu Formation) of Southern Campos Basin, Brazil, has been established based on FMI log and sidewall cores. This supports the widely held view that the Campos reservoirs are a) very big, b) very unusual, c) partly microbial, and d) lacustrine in origin. However, to date little has been published on the detail of these interpretations and nothing published on thicknesses, facies, cycles, stacking patterns, facies models and environments of deposition. This paper addresses these topics based on continuous, good quality FMI and gamma ray logs supported by thin sections from sidewall-cores.

The Aptian carbonate sediments of the Campos Basin were deposited in post-rift, sag basins during the transitional phase from continental to marine systems during the opening of the South Atlantic. Stratigraphic geometry and facies distribution are controlled mostly by extensional tectonics and relative lake-level fluctuations. The facies distribution for the Macabu Fm normally shows clastic alluvial fans close to the shoreline with carbonates basinward deposited in shallow and restricted non-marine environments.

This single well study indicates 200m of microbialite facies are encountered in the southern Campos Basin near the top of about 600m of Lagoa Feia Group non-marine carbonates (largely molluscan rudstones or coquinas). Continuous FMI and Gamma Ray logs and limited sidewall core data are used to classify FMI facies, to construct a facies model and to identify high-frequency sedimentary cycles. The FMI log is of good quality and images grain textures, sedimentary and the diagenetic structures together with information on pores and fluids. This allows the identification of 10 recurring FMI facies (Figure 1).

![Figure 1](image-url) – Ten facies based on FMI log interpretation. The scale of each image is 10cm wide and 12cm high and shows the complete dynamic image of the wall to the well.

The most common FMI facies encountered are interpreted as Autochthonous carbonates, which can be classified as laminites (laminated), stromatolites (laminated), and thrombolites (clotted). Preserved filaments, peloidal tufts, stromatolitic layering all suggest a microbial control whereas associated spherulites, ooids and stevensite suggest abiotic precipitation. No crystal shrubs are seen. Allochthonous carbonates are classified as laminated mudstones, grain to rudstones and coquina rudstones. As well as bedding and lamination erosional surfaces, some with desiccation cracks, can also be interpreted.

Based on facies relations, recurring upward facies transitions and the occurrence of erosion surfaces in the FMI log, a schematic facies model has been erected in order to understand the occurrence of the FMI facies (Figure 2). Four environments are interpreted: deep subaqueous (below storm wave base), intermediate subaqueous (below fair-weather wave base), shallow subaqueous (above fair weather wave base, very shallow conditions) and emergent (or,
Each environment has characteristic facies (Figure 2) and the facies model is used to interpret the arrangement and the stacking pattern of the cycles (Figure 3).

**Figure 2** – Schematic facies model based on FMI log for the microbialites of the Aptian succession, Campos Basin.

The logs commonly show stacking of facies in what are interpreted as shallowing-upward facies trends to emergent surfaces. Where repeated, these are interpreted as metre-scale cycles. Less commonly, deepening-up trends are seen and cycles are more symmetric. These repeated trends are then interpreted as possible cycles of shallowing or deepening related to variations in the lake level.

This early to middle Aptian interval (117 to 112.5 Ma) is made up of a hierarchy of cycles. The metre-scale, high frequency (5th order) cycles are grouped into three 4th order depositional sequences that are recognized on the gamma log. The cycle stacking and gamma log also indicate that the entire interval is represented by one regressive - transgressive 3rd Order sequence.

This work emphasises the value of good quality continuous FMI image log and other wireline logs when combined with sidewall-core and gamma ray logs. Although the facies are not as precisely defined as core based facies they enable the recognition of FMI facies, erosional surfaces, provisional facies models and sedimentary cycles.
Thursday 20 June
Session Three: Mesozoic
Non marine \textit{in situ} precipitated carbonate buildups accumulate in a wide range of terrestrial settings ranging from sublacustrine to subaerial spring environments. Precipitation can be the result of: 1) abiotic processes (evaporation, degassing, mixing of water masses supersaturated with respect to carbonate minerals); 2) biologically induced and influenced (organomineralization s.l.) precipitation in association with microbes and their biofilms; and 3) biologically controlled precipitation by organisms secreting a carbonate skeleton (e.g., bivalves, gastropods, ostracodes) but these might also be very scarce or absent according to the water extreme chemical and physical properties (hypersalinity, high alkalinity or high temperature).

In lakes, carbonate buildups accumulate in a wide spectrum of water chemistries but predominantly in hydrologically closed basins, with alkaline to hypersaline conditions, in arid climate and tectonically active settings. Carbonate buildups can be distinguished in: 1) decimetre to metre scale mounds, subparallel to the shorelines forming continuous belts traceable for hundreds of metres where microbially mediated processes seem to predominate; 2) isolated metre to decametre scale mounds located at sites of sublacustrine groundwater spring discharge, where the mixing of groundwater and lake water is the trigger for abiotic and biologically induced/influenced carbonate precipitation; 3) decimetre to decametre sheet-like to mound-shaped deposits associated with sublacustrine hydrothermal vents. In the latter case, the location of carbonate accumulation is often controlled by extensional or strike-slip faults and both abiotic and organomineralic precipitation processes might take place.

Within the subaerial spring carbonates: 1) travertine deposits are precipitated from water issuing from hydrothermal springs (temperature > 20 degrees C) and can typically drape the antecedent topography, accrete and prograde building mounds, fissure ridges, fans with terraced and smooth slopes and cascades, decimetre to several tens of metres in size, and occasionally up to hundreds of metres. In fast-flowing settings, rapid CO$_2$ degassing, cooling and evaporation seem to be the predominant mechanisms inducing carbonate precipitation. Nevertheless, microbial biofilms are widespread in such high temperature settings and often act as substrates for crystal nucleation. In slow-flowing hot-spring pools and ponds, biologically induced/influenced precipitation might be predominant associated with heat-tolerant microbial biofilms. 2) Carbonate tufa are related to flowing ambient-temperature water from freshwater springs, rivers and streams and can form barrages, dams, and cascades. In tufas, carbonate precipitation abundantly encrusts the vegetation (macrophytes, microphytes, bryophytes), and is also biologically induced by photosynthetic green algae and cyanobacteria.

A classification of the wide spectrum of carbonate microfabrics identified in non marine carbonate precipitates is proposed including: 1) micritic and microsparitic laminated boundstone, 2) clotted peloidal micrite framework and dendritic boundstone; clotted micrite also encrusts algae, insect larvae, macrophytes and microbial filaments, 3) millimetre to decimetre size laminated, fan-shaped or dendritic crystalline crust cementstone; 4) coated grains ranging from inorganically generated high-energy ooids, pisoids and microbially mediated oncoids.

Laminated and clotted peloidal micrite fabrics of inferred microbially mediated precipitation occur across the whole range of lacustrine and spring-related carbonates. They are not diagnostic of a specific depositional setting and share texture similarities with marine microbialites common in the Palaeozoic and Mesozoic geological record. Carbonate crystalline crusts seem to predominate where abiotic precipitation plays a major role, such as in lakes where mixing with groundwater or hydrothermal water occurs and in hot-spring travertine deposits, even though they often nucleate on organic substrates. However, at the microscale observation, also carbonate crystalline crusts (bladed, fan-shaped or dendritic) seem not to be exclusive of a particular depositional setting.
When observed individually, at the thin section scale, non marine carbonate microfabrics and their primary porosity cannot be linked to a specific environment of deposition resulting uncertain proxies of buildup shape, size and spatial distribution. The association of carbonate microfabrics at the centimetre to metre scale can be indicative, but not exclusive, of specific depositional environments. Carbonate precipitation seems to result from a continuum of abiotic and microbially mediated processes in settings where microbial biofilms, even if acting as passive substrates, are widely present due to the often extreme water chemical and physical conditions.

Non marine carbonate buildups have the potential to constitute excellent subsurface reservoirs for their abundant depositional porosity. However, the predictability of non marine carbonate reservoir properties is far from being understood as a consequence of the high variability and complexity of the carbonate fabrics, their porosity, spatial distribution and processes of precipitation.
Keynote Speaker: To Be or Not To Be, Microbial: Does It Matter?

Paul Wright, BG Group, Thames Valley Park Drive, Reading RG6 1PT

Differentiating microbial from non-microbial precipitates in the stratigraphic record impacts not just on the record of life on this planet, but also on how depositional environments are interpreted and potentially on how their distribution should be predicted. This is especially important when spatial analogues are absent and interpretations have to be based on understanding the mechanisms of formation. To illustrate this problem a subsurface Mesozoic lacustrine example currently interpreted as microbial will be used incorporating published and other public domain data sets.

These lacustrine carbonates exhibit a paucity of characteristic microbial features. Microbial macrostructures such as stromatolites are rare (<0.5% of thickness of logged sections), as are microbial laminites (<1%), and oncolites (<0.1%). Microbial microstructures such as “porostromate” tubes are rarely seen (<0.5% of samples studied), as are peloidal textures. Evidence of endolithic activity is also very rare. Depositional organic content is low and stable isotope analyses do not support a microbial origin. What are present are mm-cm-sized calcitic crystal shrubs and mm-sized spherulites, the former identical to forms described from a range of travertine-tufa deposits.

Mg silicates intimately associated with the carbonates suggest that the lake waters were highly alkaline (pH>9). This does not preclude microbial activity from alkaliphiles but evidence is lacking.

The carbonate textures seen are interpreted as the products of rapid crystal growth, as benthic cements and within Mg-silicate gels, from highly saturated solutions, and were more likely to have formed in shallow waters, but not necessarily in the photic or oxic zones. Sedimentological and geochemical data does not support an origin directly from thermal springs as in travertines. The two types of precipitate (crystal shrubs and spherulites) reflect specific substrate conditions. When Mg silicate gels were present, spherulites grew in the gels, their morphology controlled by the medium and by high Mg and silica concentrations, all known to promote spherulitic growth. Where the gels were not present or were less extensive, calcite crystal shrubs nucleated. The interaction of gel deposition, calcite nucleation and growth and phases of reworking and burial, resulted in irregular growth geometries at the decimetre scale and mound forms. The change from spherulites to shrubs need not reflect any change in energy levels (oolids, oncocoids to bioherms) but reflects the influence of gel distribution.
Importance of Microbial Texture for the Porosity Characterization in Microbial Carbonates

Marcelo Fagundes de Rezende 1,2, Michael C. Pope 2

1 Petrobras, Research Center, Rio de Janeiro, Brazil
2 Department of Geology and Geophysics, Texas A&M University, Halbouty Hall, College Station, TX, 77843

Microbial carbonate rocks are sedimentary deposits highly influenced by their environmental settings. Pores related to microbial textures have properties that reflect biological processes rather than mechanical sedimentation of loose grains. Thus, pore network development has a primary relation to the depositional environment, which is modified by subsequent diagenetic events. The microbial textures control the petrophysical properties based on their fundamental rock characteristics such as: microbialite size and morphology, structure packing and framework fabric. A proper reservoir evaluation must consider the analysis of the depositional texture and diagenesis and their relations to the depositional settings to better characterize microbial carbonate reservoirs. Lower Cretaceous microbial carbonate units, in some Eastern Brazilian Atlantic Basins, have complex pore structures produced by their primary framework porosity, diagenetic cements, and secondary porosity. These carbonate units form primarily of microbial carbonate deposited with mudstone, intraclast and skeletal packstone and intraclast and/or skeletal grainstone. Complex pore networks and high spatial reservoir heterogeneity result in reservoir units with total porosity ranging from 2 to 26% and permeability from less than 0.001 mD to 4.2 D. Core plugs were selected in intervals with well-defined rock properties to perform porosity, permeability and capillary pressure measurements to understand how fundamental rock properties relate to the pore network in microbial carbonates. The core measurements and rock description also were correlated to petrophysical wireline log analysis, aiming to identify stratigraphic relationships that allow the reconnaissance of rock types that link depositional or diagenetic rock properties and pore networks along the reservoirs. These pore networks formed primarily from the microbial texture, and were reduced or enhanced by diagenetic processes. The data suggest that size, morphology, heterogeneity and packing of the microbial structures are fundamental controls on the porosity, permeability and pore-throat distribution.

The size and morphology of the microbial structures, and their packing drive major changes in the pore size and permeability, whereas the heterogeneity of microbial structures impacts the primary porosity. A sample with small microbial structures, low heterogeneity of microbial structures, and loose packing has lower permeability for the same range of porosity than a sample with the same characteristics, but with larger microbial structures. In contrast, difference in the heterogeneity of microbial growth structures has more impact on porosity. A heterogeneous texture, with structures of different sizes and complex morphologies, has lower porosity than one with a homogeneous, simple texture. The heterogeneity also influences the pore-throat radius distribution, but the main control on permeability is microbial structure size and morphology. Complex microbial morphologies result in intricate pore networks with dead-end pores and tortuous pore-throats systems, which cause permeability reduction. Additionally, trends in porosity and permeability may be tracked on wireline logs in a predictable stratigraphic approach, once the relationship between pore network, microbial texture and changes in environmental conditions are defined. A well-developed microbial texture, with large simple structures, and loose packing is expected to form in optimal environmental conditions for microbial growth. This well-developed microbial texture will result in a rock type with better porosity and permeability than textures formed under poor microbial growth conditions. In these Lower Cretaceous carbonate units, the well-developed textures are characterized by large digitate stromatolites, low structure heterogeneity and loose packing, very low total gamma-ray values and low Th/U ratio. Early dolomite and silica cements also are volumetrically lower in this texture, producing photoelectric values close to calcite values. This texture has high porosity and permeability values, and unimodal pore-throat distributions. Conversely, the thinly laminated stromatolites formed in poor environmental conditions are associated with high
gamma ray values, with relative higher Th/U ratio. This laminated stromatolite texture has low porosity and permeability values. The presence of early calcite, dolomite and silica cements is favored in this facies, which cause lower photoelectric factor values. Intensely diagenetically modified intervals can also be tracked in wireline logs, since they record lithological and porosity changes that affect both rock composition and pore network. Thus, the transition between these textures will result in trends on wireline logs that can be useful identify and understand changes in petrophysical properties correlated to depositional characteristics, which can help to constrain parameters for reservoir models.
Pre- and Post-Salt Non-Marine Carbonates of the Namibe Basin, Angola

Ian Sharp¹, Klaas Verwer¹, Hercinda Ferreira², Fabio Lapponi¹, Marco Snidero⁴, Vladimir Machado², Erik Holtar³, Roger Swart⁶, Julian Marsh⁷, Laurent Gindre¹, Cai Puigdefabregas⁵, Morten Fejerskov¹

¹Exploration Research, Statoil, Bergen, Norway
²Pesquisa & Producao, Sonangol, Luanda, Angola
³Statoil, Luanda, Angola
⁴University of Barcelona, Barcelona, Spain
⁵Consultant, Barcelona, Spain
⁶Consultant, Windhoek, Namibia
⁷Rhodes University, Grahamstown, South Africa

The Namibe Basin is the southern-most of the Angolan Atlantic margin salt basins; an oblique rifted margin, essentially the conjugate to the hydrocarbon prolific Santos Basin of Brazil. Onshore outcrops are limited to a narrow (20 km wide) elongate (150 km long) coastal strip, occurring at the very edge of the South Atlantic rift. Incised drainage and an arid climate afford good outcrop conditions, allowing a unique insight into Pre- and Post-Salt successions. In this contribution we present the results of a collaborative Sonangol-Statoil study addressing the Namibe Basin. Specifically, we show 2 case studies on fault-related carbonates; 1 Pre-Salt and 1 Post-Salt.

The fundament of the Namibe Basin is composed of Precambrian igneous and metamorphic basement of the African shield. The first rift-related deposits are interbedded basalts (dated 133Ma), quartz latites and aeolian-alluvial clastics exposed in a series of tilted fault blocks. Overlying the granitic/gneissic basement and the volcanics are an unusual set of outcrops including fissure ridge and “dam and cascade” carbonates (travertines) and associated lacustrine sediments. The travertines are spatially related to extensional-transtensional faults, and typically have “cascade” morphologies, draping underlying topography. Lacustrine units are spatially confined to topographic lows, typically hangingwall basins, and are spatially limited in extent (5-15m thick, 200m to 2 km laterally). Hangingwall basin fills are mixed carbonate-clastic, including cryptalgal laminites. At 2 locations a lateral passage from travertine to lacustrine facies can be mapped. Secondary diagenesis is complex, including dolomitisation, silicification and exotic hydrothermal cements.

Post-salt non-marine carbonates are associated with a second period of igneous activity (dated 88ma). Multiple volcanic centres can be mapped, again spatially related to faults. Both subareal and submarine flows (subordinate) are exposed. In the subareal settings spring mound and fissure ridge carbonates are spectacularly developed, associated with extensional faults. Individual fracture-fed cascades can be mapped into hangingwall basins, where they pass into mixed carbonate-clastic sediments, including locally well-developed coquina facies. Diagenesis is again marked, with magnesium smectite formation, dolomitisation and extensive silicification that is spatially linked to vents.

The two case studies give an insight into the important link between igneous activity, faulting and non-marine carbonate deposition; analogy can be drawn to the enigmatic Pre-Salt reservoirs of the South Atlantic.
Lithocodium-Bacinella Build-Ups in the Lower Aptian of the SE Arabian Peninsula—Implications for Reservoir Geology

Niels Rameil, Maersk Oil, Esplanaden 50, 1263 Copenhagen K, Denmark

Lithocodium aggregatum and Bacinella irregularis are enigmatic, encrusting, now extinct microorganisms that were widespread in shallow-marine environments of the Tethys during the mid-Cretaceous. They frequently co-existed, showing an intimate association overgrowing each other. B. irregularis has been considered as a calcifying cyanobacterium by most authors, but the taxonomic position of L. aggregatum is subject of ongoing debate. Since its first description as a codiacean alga, L. aggregatum has been proposed to be of multiple (symbiotic) botanical origins, a cyanobacterium, an encrusting foraminifer, a sponge, or a calcimicrobial colony. It has also been proposed that L. aggregatum and B. irregularis are not separate taxa but represent in fact different ontogenetic stages of the same organism. Recently, a re-interpretation of both L. aggregatum and B. irregularis as ulvophycean green algae (?Order Ulotrichales) has been proposed. It has also been stated that nearly all of the “B. irregularis” occurrences reported in literature actually do not belong to this taxon, but represent irregular vesicular crusts (= “bacinellid” fabrics). Irrespective of these taxonomic complications, it is obvious that the different growth modes of this micro-encrusting consortium share many similarities with microbial carbonates.

L. aggregatum and B. irregularis are abundant in Lower Aptian carbonate reservoirs (Shuaiba Formation) of the South-East Arabian Peninsula. During parts of the Lower Aptian, these organisms took over the role of the clearly dominant bioconstructor all over the Oman platform and produced build-ups on a wide range of scales. Due to their high initial porosity, as well as frequently observed pervasive early cementation, these biogenic geobodies can have a significant influence on reservoir property variations and flow-unit geometries.

A central point of the presented study is the integration of observations from various physiographic settings along a transect over the Oman platform on a multitude of geometric scales. The observational scale ranges from seismic sections (many km), correlation of cores (100’s of m to km), outcrops (10’s to 100’s of m), rock specimens (dm-scale), down to thin-section level (cm-scale). This observational range is considered to be of fundamental significance for the assessment of Lithocodium-Bacinella geobodies and, more specific, different morphotypes.

Seismic sections obtained in Shuaiba Formation deeper ramp environments reveal km-scale, flat-based, complex geobodies that are referred to as superstructures in this study. A superstructure is composed of inter-connected mounds, each of which can attain up to 10’s of m in height and 100’s of m in lateral extent. Detailed stratigraphic sections from cores drilled through these mounds show a layered internal structure, defined by an alternation of Lithocodium-Bacinella bind–stones, rudist debris, rare rudist biostromes, and pelletal-foraminiferal wackestones to packstones. In high-energy environments of the shallow platform and the platform rim clusters of Lithocodium-Bacinella build-ups are found. The geometries and level of complexity of build-up clusters are comparable to those of the superstructures, yet on a much smaller scale (10’s to 100’s of meters). The size of discrete build-ups in these settings ranges from m-scale (internal, shallow platform) to 10’s of meters (platform rim). On the dm to cm scale, Lithocodium-Bacinella growth morphology all over the Oman Platform can be classified into six different end members (“morphotypes”).
Comparing the different examples of Early Aptian Lithocodium-Bacinella growth studied in various depositional settings of the Oman Platform, it seems appropriate to postulate a palaeoenvironmental control on the various observed geometries of Lithocodium-Bacinella geobodies and morphotypes. Possible drivers that may have influenced Lithocodium-Bacinella growth over the study area are discussed; specifically against the background of a coeval period of world-wide palaeo-oceanographic turn-over (Oceanic Anoxic Event 1a, “Selli level”).

From an applied point of view, the developed qualitative model for Lithocodium-Bacinella growth geometries allows for providing more realistic input data for reservoir modelling. On the science side, the presented results advance the understanding on how carbonate factories in Early Aptian central and southern Tethys epeiric seas reacted to global changes that probably also induced Oceanic Anoxic Event 1a. Finally, the wide range of observational dimensions documented here (km to cm scale) highlights the perhaps underestimated problem of scale bias in purely outcrop-based or core-based studies.
Microbialite Facies of Lower Cretaceous Codó Formation (Northeast Brazil): Coupled Sedimentological and Isotope Paleoenvironmental Analysis of a Potential Reservoir Rock

Anelize M. Bahniuk¹, Crisogono Vasconcelos¹, Judith A. McKenzie¹, John Eller², Almério F. França³, Sylvia Anjos³

¹Geological Institute ETHZ Switzerland
²Division of Geological and Planetary Sciences, Caltech, Pasadena, USA
³Petrobras E&P, Rio de Janeiro Brazil.

This research is devoted to improve the present knowledge of the geology of the Codó Formation, one of the best-known sequences in the Cretaceous of northeastern Brazil with have been correlated to the new major petroleum discovery in the deep waters offshore Brazil. Many approach have been used to define the microbial influence on carbonate precipitation, such as description of sedimentary facies (outcrops and drill cores), petrographic description of thin sections, and microbiofacies combined with new geochemical tools the “clumped” isotope method. Based on macroscopic and microscopic analyses, four microbialite facies, which express detailed textures and exceptional microbial fossil content, were defined. These microbialite facies, designated as stromatolite, laminae, massive and spherulite, can be related to changes in paleo-depth of the lacustrine environment as reflected by ⁸⁷Sr/⁸⁶Sr cycles, which have also been observed in the directly overlying evaporite units of the Codó Formation. Clumped isotope measurements of selected fabrics yield precipitation paleotemperatures with an average value of 37.5°C. The δ¹⁸O values of the bulk carbonate (-6.8 to -1.5 ‰ VPDB) imply precipitation from water with calculated δ¹⁸O values between -1.6 and 1.8 ‰ VSMOW, possibly reflecting precipitation from variably modified meteoric waters, whereas the δ¹³C values of the bulk carbonate (-15.5 to -7.2 ‰ VPDB) indicate a significant input of carbon derived from aerobic or anaerobic respiration of organic matter, suggesting precipitation in a semi-enclosed or isolated water body. Combined, our data allow us to interpret the evolution of the Codó Formation as occurring in a closed lacustrine paleoenvironment with alternating episodes of contracting and expanding lake levels, which led to the development of specific microbialite facies associations with varying conditions. Our evaluation confirms previous studies that the Codó Formation was deposited under warm and arid paleoclimate conditions with high evaporation. In summary, our study demonstrates that new insights can be achieved to better evaluate paleoenvironmental conditions and early diagenetic processes involved in ancient microbialite formation.
Thursday 20 June
Session Four: Cenozoic
Continental Carbonates Reservoirs: The Importance of Analogues to Understand Presalt Discoveries

Aurélien Virgone¹, Olivier Broucke¹, Anne-Edwige Held², Benjamin Lopez¹,²,³, Claire Seard², Gilbert Camoin², Rudy Swennen³, Anneleen Foubert³, Jean-Marie Rouchy², Cécile Pabian-Goyheneche¹, Li Guo⁵

¹TOTAL – Pau and Paris - France
²CEREGE - Aix-en-Provence - France
³LEUVEN University - Belgium
⁴MNHN, Paris – France
⁵CASP, UK

Recent discoveries offshore Brazil have induced a renewal of interest in the study of recent and ancient continental carbonate systems which developed in a wide range of depositional settings, reflecting aerial to subaqueous environments.

Recent and ancient continental carbonate analogs provide some keys to depict the sedimentologic/sequential pattern observed at the core scale and help in the understanding of the impact of climate change, fluid flow and water chemistry on the carbonate factory. It is noteworthy that the widespread microbial development in continental carbonate systems occurs in stratigraphic intervals typified by specific climatic and geodynamic conditions, and sometimes coincides with similar development in the marine realm. Stromatolites are more developped in high water level condition. But comparative studies between intracratonic (Recent Great Salt Lake; Eocene Green River lacustrine systems) and rift lacustrine systems demonstrates that they are more extensive on a flat substrate. The control exerted by the topography may increase during abrupt alternations of arid and humid periods, influencing the water chemistry and, accordingly, leading to the development of anoxic and/or evaporitic conditions. The key issue is therefore to understand the development of carbonate in lacustrine condition, how the sedimentary bodies and features can be preserved, and how their good reservoir properties can be maintained. High subsidence rate will influence the preservation potential of the relevant carbonate bodies, while the geothermal gradient, water chemistry or volcanic activity will impact the reservoir properties.

In addition, meteoric or thermogenic travertine deposits, are an additional carbonate product that must be considered in the evaluation of continental carbonate reservoir systems.

The large and complex pre-salt lacustrine system from the South Atlantic is thought to have been characterized by a great variability in sedimentation patterns, due to strong differences in morphostructural background, size, drainage pattern, position according to the barrier and the open sea and possible inputs of sea water for the various subbasins, as well as interconnections between them, impact of regional climate and tectonic/magmatic events. Thus, none of the recent examples considered separately may provide a strict analogue of such a complex setting, but each of them may help in a better understanding of the mechanisms involved in its formation.

Several examples of Quaternary to modern lacustrine systems i.e., the Bonneville Lake-Great Salt Lake (GSL, Fig. 1) system, the Altiplano of Bolivia and several lakes from the East African Rift, have been selected to illustrate potential modern analogues for presalt lacustrine depositional settings in the Cretaceous of the South Atlantic. This review, mostly based on data available from the literature, have been completed by new observations on the Great Salt Lake and on an ancient lacustrine system: the Eocene Green River Basin.
These new data, along with the information provided in the reconnaissance studies, show that the deposition of the marginal carbonate results from the complex interplay of different controlling parameters i.e., the physico-chemical parameters of the water, the morphology of the substrate and the rapid hydrological changes induced by the short-term “dry-wet” oscillations of the region climate that is the main forcing within endoreic lacustrine systems.

The nature of carbonate deposition differs in relation with the hydrological conditions, **algal tufa** grew during periods of highstand and salinity lowering while **microbial construction and oolite deposition** took place when salinity increased and water level lowered.

(1) **Tufa development.**

Examination of two sites of tufa development and consideration of data from analogues show that:

- carbonate deposition takes place during **lacustrine highstands** and periods of **water level stabilization** that favor growth of green algae over the benches and subaquatic slopes of the lake while the area of conglomeratic discharge are poor in algae-related tufa deposits and mostly cemented by fibrous aggregates of aragonite.

- the limited development of tufas compared to their extensive formation with reef-like accumulations at Pyramid Lake and in the Bolivian Altiplano basin, is probably due to both the **steepness of the slopes of the bordering chains** that did not permit construction of larger and gently dipping surfaces and the **intensity of erosion processes** marked by conglomeratic discharges that can prevent the fixation and maintain of algae vegetation on the substrate.

- the **morphology of the substrate** plays a major role in the development of algal carbonates, in addition to the effects of the physico-chemical parameters of the water (chemistry, temperature,…).

(2) **Stromatolitic growth and oolite deposition**

The extensive development of stromatolites and oolites are mostly forced by the physico-chemical parameters of the waters, the morphology of the lake bottom and the rapid hydrological changes forced by short-term climate fluctuations. These controls may also explain some characteristics of the carbonate deposits.

- Development of extensive stromatolitic growth associated to a great production of oolites is controlled by conditions of **high salinity during periods of lacustrine lowstands**, while reduced development of tufa may start again during short periods of water level rise and
salinity decrease.

- In addition to other parameters, the **extensive development of stromatolite-oolite carbonate platforms**, extending over 10% of the lake surface for the stromatolites and 20% for the oolitic sands implies the availability of **wide shallow shores** related in the Great salt Lake to a **smooth morphology of the lake bottom**.

- Although the construction of stromatolitic reefs and mounds is predominantly controlled by the microbial activity, they appear as **composite build-ups including recurrences of algal tufa** and may be **insect larvae constructions**. The latter are much more developed in the Eocene Gosite Basin than in the Great Salt Lake probably because species of insects are different.

- The most prominent feature is the **high variability** and the **complex organization** of the carbonate deposits that reflects the **climate forcing marked by short-term fluctuations of the evaporation/precipitation rate**. This may explain the complexity of the internal organization of the marginal carbonates that exhibits a very complex intermixing of microbial sediments, tufas and oolites.

- At each interval of time, the carbonate platform develops diachronously from the shore line were the build-ups are fossilized toward the lake were microbial growth and oolite production continue to be active and these lateral variations in the growth-erosion processes are continuously repeated through the whole period of platform building.

- As in the GSL, the preserved biota in the most of the marginal carbonates of the Green River basin is poorly diversified comprising only algae in the tufa deposits and microbial communities responsible, if we except the insect larvae. Mollusks are very rare and only present before the massive development of carbonates. This suggests the construction took place in an **environment subject to a significant ecological stress, may be due to saline conditions** as also suggested by the presence of evaporites in the basin center.

(3) Travertine development and (4) evaporites should be taken in account to reconstruct a whole picture of the continental carbonates.
Microbialites of the Eocene Green River Formation as Analogs to the South Atlantic Pre-Salt Carbonate Hydrocarbon Reservoirs

H. Paul Buchheim¹, Stanley M. Awramik²

¹Department of Earth and Biological Sciences Loma Linda University, Loma Linda, CA 92350
²Department of Earth Science University of California, Santa Barbara, CA 93106

The Eocene Green River Formation stretches across 350 km of Wyoming, Colorado, and Utah is nearly 2000 meters thick, and contains what may be the richest record of lacustrine microbialites. It was deposited in four continental basins within a foreland basin associated with the Cordillearan thrust belt. Stromatolites dominate, but oncoids, thrombolites, and tufa-like microbialites occur. Most microbialites occur in laterally extensive biostromes that have the facies association of ooids/flat-pebble conglomerate, microbialite, and kerogen-rich laminated mudstone (oil shale) (Figure 1). The facies association forms pronounced stacking patterns or parasequences of microbialite biostromes that were deposited on a low-gradient lake bottom. Some of these biostromes can be traced for more than 50 km.

Multi-meter-size bioherms (Figure 2) occur in the northwest corner of Green River Basin and occupy an aerial extent of over 2000 km². The bioherms are composed of clusters of meter-scale columnar and domical stromatolites, and tufa. The 10-30 m thick bioherms are composed of stacked, 1-3 m-thick successions of oolite and grainstone, microbialites, wackestone, and carbonate mudstone. Evidence of spring activity associated with these bioherms includes tufa-filled fractures, sand-tufa stratigraphically below some of the bioherms, and tufa-like microbialites. In Utah, a bioherm is a productive hydrocarbon reservoir buried at a depth of 1400-1500 m. The bioherm is composed of various beds of oncoids, carbonate mudstone, mollusk coquinas, and wackestone.

The various microbialite facies associations and even spring-associated facies occur in specific stratigraphic relationships and their basinal and stratigraphic occurrence can be predicted. They are related to lake phase (under-filled, balance-filled or over-filled), water depth and energy, basinal location (margin to lake center), lake-bottom gradient (low to high gradient), and lake chemistry (fresh to saline). In addition, calcium saturation (in terms of calcium carbonate) is critical for the abundant and rapid growth of microbialites. For example, microbialite growth and accumulation is essentially absent during hypersaline phases of the lake, while their growth is pronounced and rapid during lake expansion (associated with flooding surfaces) when calcium input is at its highest.

Published data detailing the pre-salt lacustrine carbonates of the South Atlantic are limited; however, the “microbial” carbonate reservoirs are composed of “arborescent shrubs” or “framestone fabrics . . . shrub-like features that formed rigid frames” (Dorobek, et al., 2012). These structures are found associated with ooids, spherulites, lithoclasts, and composite grains. There is debate as to the biogenic origin of these fabrics and the jury is apparently still out on this. Similar arborescent shrubs (Figure 3) occur in the stromatolites of the Green River Formation in biostromes and larger microbial bioherms (Figure 4), suggesting that microbial influence is important to their formation.

If one moves away from microbialites sensu stricto to a broader or sensu lato interpretation of microbialites that includes microbially-influenced tufa and travertine, the Green River Formation becomes even more interesting. There are a number of occurrences of tufa-like stromatolites associated with bioherms, spring deposits, and spring mounds.

The Green River Formation is probably the best analog for the large lake systems that formed with the opening of the South Atlantic. Although not considered a rift basin, the physiographic nature of the Green River Basin is similar to the “sag” phase in that it was a very broad, rapidly subsiding basin, structurally hinged on the north with significantly greater subsidence along reverse and thrust faults on north side of the Uinta Mountains. The Green River lakes were...
saline-alkaline (bicarbonate lakes) as indicated by trona evaporates and the stevensite clays (both only occur in saline-alkaline lakes). Volcaniclastics in the form of abundant tuff beds, and dominantly volcaniclastic sandstones and claystones dominate some facies of the Green River Formation and grade laterally into the carbonate-dominated lake facies. And now that we have found abundant “arborescent shrubs” associated with Green River microbialites, both in biostromes and bioherms, we are confident that the Green River Formation will continue to provide many additional and significant insights into better understanding the pre-salt lacustrine systems.

Figure 1. Biostrome lithofacies association is composed of basal stromatolite, kerogenous-mudstone, and mud-cracked dolomicrite.

Figure 2. Bioherm at Little Mesa, northwestern Green River Basin near LaBarge, Wyoming, about 30 m thick.

Figure 3. “Arborescent shrubs” occur in some microbialites of the Green River Formation, very similar to the pre-salt features. Scale in cm.

Figure 4. Bioherms such as the one illustrated reach up to 4 m thick and 8 m in diameter.
Microbial Oolites: Rock but Not Necessarily Roll

Cody R. Miller¹, William Martindale², Noel P. James³

¹Chevron Energy Technology Company
²W. Martindale Consulting
³Queen’s University

The importance of microbial communities in carbonate depositional and diagenetic processes has become increasingly apparent within the past decade. High ion concentrations in bacterial mucus promote precipitation of calcium carbonate and Mg-silicates, including ooids that are produced in situ and without the necessity for grain movement. Such particles are known in pre-salt lacustrine carbonates along the south Atlantic margin, the middle Miocene Nullarbor Plain in southern Australia, and the Mississippian Frobisher Formation in Saskatchewan, Canada.

Middle Miocene palustrine ooids located in the Nullarbor Plain, southern Australia, demonstrate the importance of microbial communities and soil processes in the genesis of spherically laminated grains. The ooids are < 2 mm in diameter and share an uncanny resemblance to their marine counterparts. The majority of these particles are located in decimeter-scale microkarst cavities underlying the surface of the Plain. Ooid nuclei are peloids composed of dense minibicrite, charophyte fragments, exopolysaccharides, and rare algal filaments. Peloids likely formed via microbial binding of recently deposited lacustrine sediment, both inside the underlying microkarst cavities and on the surface. Such peloids are encapsulated in thin and multigenerational laminations that construct the spherical cortex. Individual laminae are composed of degraded minibicrite crystals and complex arrangements of encrusting palygorskite and sepiolite nano-fiber mats. Meniscus fabrics and small spherical pores and grains dominate the microstructure in these Mg-silicate mats and represent preservation of pre-existing microbial communities.

Cortex generation is interpreted as an annual process with regular alternations in soil hydration states intimately linked to seasonal variations in rainfall. Ooids were encased in organic mucus that bound and concentrated Mg²⁺ and Si⁺ ions from alkaline pore water during wet seasons. This resulted in Mg-silicate gels that completely covered individual ooids. Gel dehydration, consequential to succeeding dry seasons, resulted in precipitation of palygorskite and sepiolite nano-fibers. Annual seasonal rainfall variations and soil moisture created conditions in which microbes produced individual laminae that over time formed a multigenerational ooid cortex. This process generates spherically coated grains in situ, without the prerequisite for grain movement.

Microbial ooids are not unique to the Nullarbor Plain and have been identified in other geographic and temporal settings including the Mississippian Frobisher Formation in the Williston Basin, Saskatchewan, Canada. Oolite sequences can be 10's of metres thick and may host commercial quantities of hydrocarbons. Frobisher Formation oolites had previously been interpreted as marine in origin; however, more detailed investigations have revealed that many oolite occurrences are terrestrial in nature, precipitated in a semi-arid setting. Frobisher ooids exhibit concentric cortical micrite laminations like those from the Nullarbor, and as such are interpreted to have formed via similar microbial processes. Grains may exhibit desiccation cracks and multigenerational coatings, resulting in complex, cm-scale pisoids. In rare instances, asymmetry of compound grain suggests upward flow of pedogenic fluids during periods of desiccation (“pisoid comets”). Differences in the geometry and composition of Frobisher and Nullarbor ooids are likely a function of ion availability in solution and climate. Frobisher ooids are exclusively calcitic, reflecting the semi-arid carbonate-dominated calcrete environment in which they precipitated. Nullarbor Plain ooids in contrast, were precipitated from Mg silicate-rich waters in a palustrine setting.
In situ formation of ooids, pisoids, and oncocoids relies upon microbial communities to uniformly precipitate minerals that result in spherical grains. Hydrated Mg-Si or Ca gels and extracellular polymers produced by mucus-forming bacteria encapsulate grains and serve as nucleation sites for mineral precipitation. Bacterial mucus decreases diffusion, concentrates bound ions from solution, and provides suitable nucleation sites that favor mineral precipitation by overcoming kinetic inhibition. During periods of low rainfall, mineral precipitates concentrate in dehydrated mucus gels. The mineral phase precipitated depends upon the chemistry of pore waters in which the ooids form. In highly alkaline lakes and soils where Mg$^2+$ and Si$^+$ ions are abundant, the common mineral precipitates are palygorskite, sepiolite, and stevensite. Calcareous soils in highly evaporative settings, such as calcretes, have pore waters dominated by Ca$^{2+}$ ions and accordingly calcium bicarbonate is the main precipitate in these conditions. The mineralogy of cortical laminations reflects the chemistry of lake and soil pore waters and thus is a valuable tool in the reconstruction of ancient lacustrine, palustrine and calcrete environments.
Controls on Lacustrine Microbialite Distribution in Great Salt Lake, Utah

R.L. Baskin¹, N.W. Driscoll², V.P. Wright³

¹University of Utah, Salt Lake City, UT, USA
²Scripps Institution of Oceanography, La Jolla, CA, USA
³BG Group, Reading, UK

Recent geophysical surveys and physical sampling of the benthos of Great Salt Lake, Utah, provide detailed information on the occurrence, distribution, size, shape, and spacing of individual microbialite structures as well as larger morphologic forms. Integrated geophysical surveys, physical sampling, video, and in-situ observation reveal that microbial bioherms vary from dispersed to laterally-connected coalesced domal forms throughout shallow areas of the lake. The majority of bioherms range from above water-surface exposures to depths of over 5 meters. Individual forms typically are circular to oblate and range from 0.5m in relief with diameters ranging from 0.5m to 2m. Transitions between non-bioherm areas and bioherm-populated areas range from gradual to abrupt and from dispersed to highly clustered distributions. Where abrupt changes are observed, CHIRP sub-bottom data show topographic structural control as a result of faults, folds, or monoclinal structures. Linear distributions of bioherms align parallel to primary structural and bathymetric controls. In some locales, bioherms are buried beneath fine-grain lacustrine sediments.

A rock-filled causeway constructed in late 1950’s, subdivided GSL as well as the microbialite population. The effect of lake modification and salinity changes in the subdivided lake are evident in the bioherm populations as exposures and samples of microbial bioherms from the south part have an abundance of surface-based phototrophic communities and show an increase in dissolved oxygen near the bioherms, indicating photosynthetic primary production. In shallow-water margins of the north part of the lake, the bioherms are bleached and visually devoid of life. Salt crystals precipitated from the hypersaline water mantle large expanses of bioherms and no increase in dissolved oxygen near the bioherms was observed. Widespread die-off of bioherms communities suggests that environmental conditions have exceeded the range that microbial bioherm-forming communities can tolerate. Initial correlation of sediment acoustic characteristics with the acoustic base of microbial bioherm development places initiation time at less than ~12.5 ka. Microbialite samples from the south and north parts of the lake have been submitted for radiometric age determination.

Exposed microbial bioherms in the north part of Great Salt Lake, Utah (A); and south part of Great Salt Lake, Utah (B).
Side-scan sonar image showing transition from low-acoustic reflectivity, fine-grained sediments (right side of image) to highly-clustered, highly acoustically-reflective microbial bioherms (left side of image).
Lacustrine Carbonate Facies in Extensional Settings: Case Studies from Lakes in East Africa’s Great Rift Valley

C.A. Scholz¹, M.K. Hicks², J.E. Hargrave³, A.J. Morrissey¹

¹Syracuse University
²Onondaga Community College
³Southern Utah University

Microbial carbonates and associated facies are recognized in a variety of non-marine settings. Lacustrine carbonates occurring in extensional environments may host significant hydrocarbon deposits, as evidenced by recent discoveries on the South Atlantic margins. The East African Rift (EAR) offers recent analogues for lacustrine carbonate deposits in different structural, climatic and depositional settings. Carbonate accumulations may be enhanced in magmatically-active rifts, due to increased discharges from subaerial and sublacustrine springs and high solute loadings into lakes. Here we present examples of microbial carbonates from two end-member magmatic rifts: 1) Lake Turkana, now occupied by a large, alkaline, mildly-saline lake in the arid north Kenya Rift; and 2) Lake Kivu, a deep meromictic lake in the humid and elevated section of the western branch of the EAR.

Both the Lake Turkana and Lake Kivu Rifts are comprised of asymmetric half-graben basins, where subsidence is accommodated mainly on steeply-dipping border faults with high footwall mountains. The variability in slopes and margin morphology around the basin substantially impacts local siliciclastic sedimentation rates in the lakes, which in turn affect the substrate and nucleation of carbonates. Lake Turkana is ~100 m deep, experiences >2000 mm/yr of evaporation due to its low elevation (361 m) and arid climate, and has been hydrologically closed for the past 4000 years. Lake Kivu is 480 m deep, rests at an elevation of 1463 m in a region with high precipitation (>1000 mm/yr), and consequently is hydrologically open (flowing south into Lake Tanganyika). Given the high catchment relief, both basins are mixed siliciclastic-carbonate systems.

Carbonate lithofacies observed onshore around southeastern Lake Turkana include carbonate mudstone, wackestone, ostracod and gastropod grainstone/packstone, and boundstone. In southeast Turkana three stromatolite mounds are observed collocated with extensional faults, and are interpreted as spring deposits. Microbialites from Turkana contain a variety of fabrics. Individual oncoids are the most common carbonate deposit and nucleate on basaltic pebbles, cobbles, or on shell fragments. In some areas individual oncoids coalesce up-section forming biostromes, and oncoid diameters also increase up-section from ~0.5-40 cm. Individual microbialite laminae are variable, and can show stromatolitic, spongy, dendritic, branching, and thrombolitic fabrics. Mesostuctures can be subdivided into tussocky, chaotic/thrombolitic, laminated, micro-columnar stromatolite, and branching fabrics; in some instances they contain microbial filaments.

Lake Kivu also has carbonate deposits in the form of encrustations and oncoids that appear along the lake’s shoreline and near subaerial hot springs. Localized paleo-hot spring deposits are observed along the southeastern shore of the lake. As the lake is near its maximum late-Pleistocene and Holocene highstand stage, most carbonate deposits are now drowned, unlike those observed in the present-day Lake Turkana Rift.

A variety of processes influence microbial carbonate sedimentation in the East African Rift lakes:

- The relative position within the half-graben structural framework plays an important role. For instance the flexural margin promotes deposition and preservation of deltaic facies, and is also the site of rapid lateral migration of the shoreline during lake level shifts, which can destabilize the carbonate factory.
The record of carbonate sedimentation and preservation in deep water core samples shows that there are time periods when lake level stability, water column chemistry, and limnologic conditions are most ideal for generation of lacustrine carbonates.

Substrate character and relative inputs of detrital material are key controls on facies variability on length scales of ~100-1000 m along the lake shorelines.

Climate variability is the first-order control on water column chemistry and lake level on time-frames of $10^2$-$10^4$ years.

Rift magmatism promotes hot spring activity and solute loading allowing carbonate precipitation on a variety of temporal scales.
Microbial Carbonates - A Sampling and Measurement Challenge for Petrophysics

Patrick Corbett¹, Leonardo Borghi², Zeyun Jiang³, Haitao Wang³, Felipe Yuji², Alessandra Machado²

¹Heriot-Watt University, Edinburgh
²UFRJ, Rio de Janeiro
³Heriot-Watt University

Microbial carbonates (microbialites) have recently become systems of renewed interest for the oil and gas industry after the discovery of more than 15 Billion Barrels of Oil Equivalent in Pre-salt reservoirs of the Santos Basin, Offshore Brazil. These reservoirs include carbonate intervals of possible microbial origin.

In Brazil, there are a number of microbialites ranging in age from the Proterozoic (e.g., Irecê Basin; Pereira, 2012) to the Recent lagoonal stromatolites on the coast of Rio de Janeiro State (e.g., Lagoa Salgada, 300-3,500 yrs BP; Iespa et al., 2011) – all these potential microbialite reservoir analogues.

Biosediments of microbial nature are complex cyanobacterial colonial structures variously including biofilms, mats, mounds, oncolites, stromatolites, thrombolites, dendrolites, leiolites, tufas, and travertines, which can vary in size from a few centimetres in size (oncoids, spherulites and small single stromatolite columns) to large structures several metres across (bioherms and biostromes). For petrophysicists, these structures present great challenges as traditional petrophysical measurement volumes (probe, plug, whole core and log investigation volumes) may or may not be appropriate statistical support volumes to satisfy the conditions for representative elementary volumes, over and above the normal complexity in carbonate pore systems (Corbett et al., 1999). The use of (geo)modelling has driven a greater appreciation of the need of the petrophysical community to recognise the demands of geostatistics – that properties should have appropriate support volumes and be locally stationary. Microbial sediments present major challenges if such considerations are fully taken into account.

In this paper we consider for discussion: bioherms with large (Conophytoida, Kussielida and Gymnosolenida; Fig. 1) and small, digiform (Jurussania sp.; Fig.2) columnar stromatolites from the Neoproterozoic Una Group, Irecê Basin (Pereira, 2012); and stromatolite–thrombolite biostromes (Lagoa Vermelha; Fig. 3) from some of the Recent lagoons in the Rio de Janeiro State coastal area (Região dos Lagos, RJ) to address the general aspects of undertaking petrophysics in these systems.

Figure 1: Large colonial bioherm from the Neoproterozoic of the Irecê Basin, Bahia, Brazil (photo left and line drawing right) – the latter identifying a complex association of internal stromatolite columns at a scale larger than log measurements. How would you determine the effective property of such a structure?

In each case described, there is – or has been – significant porosity development of various primary and secondary natures. Primary structure is often preserved, in some form, and will exert a control on the representative elementary volumes needed for statistically valid pore characterisation.
Figure 2: The digiform stromatolite (*Jurusania* sp.)- from the Neoproterozoic of the Irecê Basin, Bahia, Brazil. Right, oblique view; centre, micro-CT view; left, plan view. Note complex structure at the core plug and wireline log scales. How would you go from plug to log scale in this material?

Figure 3: Stromatolite-thrombolite structure from the Recent Lagoa Vermelha, Rio de Janeiro State, Brazil. Porosity is variously developed throughout this structure as a result of the depositional and growth characteristics of the stromatolites and other organisms. Note the challenge presented for plugging this sample – where would you take a sample? The right hand image shows a 3-D representation of the porosity generated by image analysis of a CT Scan.

Primary and secondary process leads to many types of porosity development – both intra- and inter-granular in nature. As well as the grain scale porosity, there is also primary ‘biostructural’ porosity (shelter, cavity, boring) as well as later diagenetic development of vugular or secondary porosity to consider. Describing porosity is a fundamental challenge as the many porosity types typically present will each have their own connectivity issues to consider with respect to understanding, modelling and predicting permeability and or electrical conductivity.

In this paper, we will present some early thoughts on a more complete porosity description and characterisation for microbial carbonates, considering the role of micro-CT and geostatistics to build nested models for modelling the various petrophysical parameters that are required for reservoir description and characterisation (permeability, $k_V/k_H$, relative permeability, capillary pressure, formation factor, resistivity index, NMR response, etc.). We show that petrophysics in biosediments is invariably a complex mixture of measurement and models and posit that petrophysical description of biosediments needs special attention and development of new workflows.
3D Visualization and Quantification of the Porosity Network in Travertine Rocks

S. Claes¹, J. Soete¹, H. Claes¹, M. Ozkül², R. Swennen¹

¹Geology, Earth and Environmental Sciences, KULeuven, Celestijnenlaan 200E 3001 Heverlee, Belgium
²Pamukkale University Engineering Faculty Dept. of Geological Engineering, Kınıklı campus 20070, Denizli-Turkey

Studies in sedimentary and petroleum geology often concern the description of porosity types in order to characterize petrophysical properties: e.g. porosity, pore connectivity and permeability. This requires a quantitative geometric description of the complex (micro)structure of the rocks. Due to progress in X-ray Computed Tomography (CT), rapid, non-destructive, high-resolution 3D examination and analysis of almost any kind of material, including earth and soil materials is currently available in practice.

Most traditional pore classification systems in earth sciences rely on subjective 2 dimensional (2D) descriptions based on thin section images [Choquette and Pray, 1970; Lønøy, 2006; Lucia, 1995]. However complex porosity systems, such as encountered in carbonate sediments, require 3 dimensional (3D) information in order to obtain reliable estimations of advanced petrophysical parameters. Because monomineralic travertines cover a wide range of porosity types, from micro- to macro (vuggy) porosities, these rocks have been chosen as case study.

Cores are primarily scanned with a medical CT scanner, the Siemens Somatom. In this study the cores have a diameter of 10 cm and are between 10 and 30 cm long. The main disadvantage is that the resolution of these scans is limited to 0.5 mm in 3 dimensions. This is why in a next step plugs (2 cm diameter and 4 cm long) are drilled and subsequently scanned using microfocus CT. Samples are scanned at a resolution of (12 μm)³ using a General Electric nanotom system. Resulting segmented slices are analyzed in order to calculate several shape parameters such as form ratio (based on L, I and S - L is assigned to the longest dimension, I is the longest dimension perpendicular to L, and S is perpendicular to both L and I) and compactness. Based on the results of this analysis and on particle classification systems [Blott and Pye, 2008], a pore classification is proposed. Figure 1 presents an overview based on the form ratio’s I/L and S/I. In this diagram 5 shape classes are defined: rod, blade, cuboid, plate and cubic shapes.

Figure 1: Diagram of the theoretical pore shapes based on I/L and S/I form ratio's

This approach allows comparing the porosity network of different travertine facies in an objective way. Figure 2 shows the pore system in a reed (A) dominated and shrub-like (B) dominated facies. The porosity network of the shrub-like dominated facies is clearly dominated by one large pore. This feature also has an important impact on the effective porosity and permeability of these samples. Shrub-like dominated samples have typically higher values (22% Ø and around 6000mD klinkenberg corrected gas permeability) compared to other facies...
types (15% Ø and around 5mD klinkenberg corrected gas permeability).

To analyse the pore shapes, pore bodies have to be defined in order to calculate correct L, I and S dimensions. This is especially important in case of the shrub-like dominated facies, because it is impossible to describe the shape of such a complex pore. Figure 2C depicts the different pore bodies.

Figure 2: Porosity network in travertine rocks (label colours correspond to connectivity; medical CT scan (10cm diameter)); A: reed dominated facies; B: shrub-like dominated facies; C: Pore bodies of sample B.

This approach allows to separate different types of pore shapes as well as to assess the anisotropy of the porosity in the sample by using the orientation of the longest dimension. The same patterns of results are seen for the micro-CT scans. On a smaller scale the porosity network of the shrub-like dominated facies remains highly connected as shown in Figure 3.

Quantification of the different recognized pore shapes allow identifying the pore characteristics of different types of depositional environments on an objective basis (Table 1).

<table>
<thead>
<tr>
<th>Sample</th>
<th>Rod</th>
<th>Blade</th>
<th>Plate</th>
<th>Cube</th>
<th>Cuboid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reed dominated</td>
<td>0.23</td>
<td>0.17</td>
<td>0.35</td>
<td>0.07</td>
<td>0.18</td>
</tr>
<tr>
<td>Shrub-like dominated: large core</td>
<td>0.05</td>
<td>0.03</td>
<td>0.20</td>
<td>0.34</td>
<td>0.38</td>
</tr>
<tr>
<td>Shrub-like dominated: plug</td>
<td>0.004</td>
<td>0.006</td>
<td>0.10</td>
<td>0.66</td>
<td>0.23</td>
</tr>
</tbody>
</table>

Table 1: Shape distribution based on 3D datasets of different travertine samples.

Figure 3: Porosity network in travertine rocks (label colors correspond to connectivity; Micro-CT scan(2cm diameter)); A: shrub-like dominated facies; B: Pore bodies of sample B.

This technique allows visualization and quantification of the complex porosity network in travertine rocks. When comparing petrophysical parameters of different facies types it becomes clear that shrub-like facies has systematically higher porosity and permeability values. This is also confirmed by the 3D visualization of the different porosity networks. The use of CT imaging enhances the objectivity of the description of the porosity network.
Poster Presentation Abstracts
Microbial Textures, Facies and Geobodies: Outcrop Analog with Features Ranging from Mm-Scale to 100 m-Scales in Precambrian-Cambrian Carbonates, Qarn Alam, Oman

Peter Homewood¹, Said Al Balushi², Monique Mettraux¹, John Grotzinger³

¹Geosolutions Trd Gan, France
²PDO, Muscat, Oman
³Caltech, Pasadena, USA

Late Proterozoic to Early Palaeozoic microbial carbonate rocks, which are analogous to the Ara Carbonate “Stringer” reservoirs of the South Oman Salt Basin, are exposed by surface-piercing salt domes in Central Oman. At the Qarn Alam salt dome, field observations on facies, facies relationships, and depositional geometries such as channels, scour and fill etc., indicate that primary depositional attributes have been extremely well preserved. Analytical studies have shown that only a very minor diagenetic overprint has occurred in these rocks since the Early Cambrian, during burial, uplift and exposure. This is in contrast to strong burial diagenetic modifications reported from the Jabal Majayiz salt dome nearby. The analytical results confirmed that the sedimentary features and geometries that can be observed on outcrop are indeed primary and depositional in origin, with partial preservation of several different types of primary porosity. Depositional scenarios (facies models) are reconstructed from facies, depositional geometries, high frequency stratigraphic cycles and cycle stacking patterns. Although the outcrops are limited to several hundreds of metres laterally, the high-resolution stratigraphic architecture allows establishing geobody-scale distributions of specific, facies-controlled, porosity types.

A number of large blocks at Qarn Alam show similar “Ara Carbonate type” microbial facies that are organised in laterally extensive, laminit-stromatolite-thrombolite shallowing-up and emersive cycles (Figure 1). The thicker, more complete facies succession measures 7-10m in thickness, whereas several less complete, “base truncated” cycles range from 2m down to 0.5m in thickness. From bottom to top, within cycles, the facies succession comprises:

A: Planar Laminites; B: Crinkly Laminites; C: Crinkly Laminites and Stromatolites with incipient clotted texture; D: Layered to domal Thrombolites; E: Massive Thrombolite; F: “Bushy” radiating digitate Thrombolite; G: Caliche crust, Breccia and Neptunian dykes; H: Thin-beded Dolomites, Evaporites and Collapse Breccias; I: Finely laminated and commonly silicified Stromatolites. Thicker cycles contain complete A to I facies sequences, whereas thinner cycles start with facies D or E Thrombolites that overlie a previous cycle with an erosional contact on Bushy Thrombolites, Karst features or Evaporites (F, G, H).

Laminate and stromatolite facies are composed of irregular, current reworked detrital carbonate grains, or simple to “tufted mat” layers, comprising mm-size clots and larger clumps of clots that are composed of micritic peloids. Thrombolite mesoclots are either composed of layered clumps of clots (“layered thrombolite”) or are bushy, branching structures of a precursor form (“bushy thrombolite”). Although the microbial origin of these rocks is hardly in doubt, full confirmation is provided by the fossilisation of forms such as filaments, sheaths and coccoids, as well as preservation of alveolar, honeycomb growth texture of EPS, both in the laminites and in the thrombolites. The deposition of these facies resulted from trapping and binding controlled by microbial mats for Facies A, B and C, but with an increasing role of growth and mineralisation of microbial EPS in the thrombolite facies (C, D, E, F). Growth of more complex forms such as sponges may have contributed to the development of the “bushy” shaped mesoclots of facies F.

Although in general the facies succession is regular with no obvious erosional hiatus, mapping of the limit between the massive or bushy thrombolites (Facies E, F) and the layered thrombolites (Facies D) reveals channel incisions cutting into the layered thrombolites. The depths of incisions range from 0.5m to 2.5m, by 2m to 5m wide. The upper part of the layered thrombolites shows scour-and-fill features that are several-cm deep by 10-20cm wide. The scours are draped or filled by clotted microbial laminae. Layers of darker and lighter colour that
correspond to clotted fabrics (darker) and highly porous microcrystalline dolomite (lighter) display a double cyclicity of thickness variation (mm scale laminae, 5-10cm scale bundles of thicker or thinner laminae). Caliche crusts, neptunian dykes and karst pockets clearly record emersion at the top of the bushy thrombolites.

The shallowing-up facies sequence may be interpreted to result from progradation under one or the other of two alternative shoreface-shoreline models. If the bushy thrombolites of Facies F are interpreted to record a high-energy environment, then the simple progradation of a shoreface profile overlain by emersive sabkha deposits is suggested. Under an alternative, low-energy scenario, the layered thrombolites may record progradation of tidal flat deposits incised by tidal channels and the bushy thrombolites may indicate a low-energy higher salinity lagoonal system landward of the shoreface, followed by a sabkha environment (Figure 2). The thrombolites and grainstone shoreline sediments of the Great Salt Lake at Lakeside (Utah) provide a recent to modern analog for the bushy thrombolites of Qarn Alam.

The stacking of successive cycles, combined with progressive base-truncation of facies successions, suggest a stratigraphic seaward-stepping pattern, possibly overlain by one or two landward-stepping cycles at the top. The regular pattern of facies succession in these cycles constrains a laterally continuous layering at the scale of geobo.

dies. The layering of very different porosity types (preserved in the laminites and thrombolites) together with the patchiness of facies distribution illustrated by the facies models, provide analog features that may be incorporated in grid-cell models.

Figure 1: Stratigraphic sections and composite stacking pattern from blocks 4 and 6; large letters = cycles; small letters = facies; numbers indicate samples for laboratory analyses. Scale: Unit A = 6.5m.

Figure 2: Facies model comprising low-energy, prograding tidal flats, tidal channels, saline lagoon and sabkhas. Horizontal scales: 100m’s x km’s. Vertical scale: 10m’s.
Facies and Reservoir Characterisation of a Terminal Neoproterozoic Carbonate-Platform Margin Escarpment, South Oman Salt Basin

Joachim E. Amthor, Abdulghani Gaghman, Simon Tull, Michael Ruf, Martin Healey, Petroleum Development Oman

The Terminal Neoproterozoic to early Cambrian Ara Group of the South Oman Salt Basin comprises at least six 3rd-order cycles of carbonate to evaporite sedimentation in the center of a tectonically active basin. The salt basins formed (and were later deformed) during transtensional and transpressional local tectonics within a compressional plate setting. The main reservoirs occur in dolomitized carbonate platforms ('Ara Carbonate Stringers') which are fully encased in evaporites (mainly anhydrite and halite).

A recent oil discovery in a > 400m thick sequence of Ara carbonates without intervening evaporites has highlighted the range of stratigraphic play types and lateral facies variations to be encountered in the Ara Salt Basins.

Seismic data show the stacked sequence as a prominent transparent package that thins westward. Towards the east, the package is characterised by a steep transition into the deeper basin. This prominent carbonate escarpment strikes NE/SW, following the underlying basement trends, and is dissected by NW/SW trending faults which play an important sealing role. The available well and core data reveal depositional facies that indicate the presence of a highly productive microbial boundstone factory.

Characteristic facies include a variety of stromatolite and thrombolite boundstones and associated grainstones, oolitic and intraclast pack/grainstones, calcite and pisod-dominated facies with tepee structures. In particular, isopachous stromatolites and pisolitic units can be regarded as indicator facies, as they have not been observed to date in typical stringer carbonates.

Diagenetic elements that are present and which have altered and/or obliterated the depositional facies are: pervasive dolomitisation, evidence for multiple episodes of dissolution and brecciation during periods of subaerial exposure, isopachous and fibrous early diagenetic (marine) cementation and fault-related dissolution and cementation. The depositional and early diagenetic matrix complexities are compounded by fault and fracture related processes which have generated locally enhanced matrix permeability.

Permeability is the key to understanding reservoir behaviour of this highly layered, heterogeneous reservoir. Well test permeability is orders of magnitude larger than plug-scale permeability due to the influence of large-scale vugs and micro-fractures. Permeability is modelled by integrating core, log (NMR), facies, rock-fabric and well test data within a sequence stratigraphic framework and according to a conceptual model of unconformity-related high-K zones.

“Facies-based” approaches (i.e. Dunham) are not useful in characterising and modelling the petrophysical properties of heterogeneous microbial reservoirs. Instead, we recommend the use of rock-fabric based approaches.
Neoproterozoic Microbialites in a Frontier Basin: The Rasthof Formation (Cryogenian), Northern Namibia

E. Le Ber¹, D. P. Le Heron¹, B. A. Vining², F. Kamona³

¹ Earth Sciences Department, Queen’s Building, Royal Holloway University of London, Egham, Surrey, TW20 0EX, UK
² Baker Hughes, Bentley Hall, Blacknest, Alton, Hampshire GU34 4PU, UK
³ Geology Department, University of Namibia, Windhoek, Namibia

Producing Neoproterozoic strata that occur in Oman, Russia and China demonstrate the potential of Precambrian microbial sediments to generate significant hydrocarbon accumulations. Compared to recently discovered microbialite-bearing petroleum systems from offshore Brazil, Precambrian microbialites pose a different range of challenges. These include the nature and origin of associated source rocks, the precise age of the deposits, and the geometry of microbial reservoirs. Many of these challenges can be tackled by sedimentological outcrop analogue work.

The Rasthof Formation, of Cryogenian age, is a "cap carbonate" sequence that was deposited in Namibia in the aftermath of the Sturtian glaciation. It commences with a ~10 m cap dolostone, followed by a thicker ~120 m microbial member. This formation may belong to a self-contained petroleum system in the frontier Owambo Basin (northern Namibia), yet remains comparatively little described at outcrop. Diverse and unusual microbial facies crop out over hundreds of kilometres along the edges of the basin. In this poster, problematic issues such as microbialite geometries and their interpretation are addressed.

At the type section of the Rasthof Formation, a 60 m thick set of folded and contorted microbial mats is overlain by localised individual growths. The latter include dm sized domes, columns and branching columns (Fig. 1) geometries, occurring over a 40 m thick interval. In the folded mats, microbial communities were systematically overtaken by sedimentation, forming a well-laminated fabric. Relative abundance of microbial communities compared to sedimentation may have allowed the development of a more vertically continuous framework (Fig. 2). The microbial communities were then able to build up vertically rather than laterally. Upsection, microbial carbonates are succeeded by massive dolomite. Using macro- and microfacies description, we propose a model that explains the factors prompting both the development and demise of these stromatolites on this ancient carbonate platform.

Figure 1. Field picture (left) and sketch (right) of branching columns from the Rasthof Formation.
Figure 2. Different stromatolitic facies. A. Typical well laminated fabric and B. sketch. This fabric does not generate vertical growths. C. Laminated fabric with a continuous vertical microbial framework and D. sketch. Vertical continuity of the microbial framework allowed the development of vertical growth such as domes or columns.
Controls on Microbial-Sponge Buildup Development (Bajocian, NE Spain)

Marc Aurell, Beatriz Bádenas, Department of Earth Sciences, University of Zaragoza, Spain

In this work we present a comparative analysis of the geometry and framework of two types of Bajocian (Middle Jurassic) microbial-sponge buildups, developed in two areas of the Iberian basin (NE Spain). They have thrombolitic fabric (i.e., clotted and non-laminated microbialites) and include a variable proportion of siliceous sponges. Cavities are filled by micritic and micropeloidal internal sediment, sometimes forming geopetal structures. The main goal of this study is further understanding on the main factors controlling the development of these types of microbial dominated carbonates, and could be potentially applicable for reservoir including marine microbial buildups developed in open platform areas. The results are based in extensive outcrop and facies analysis in two Iberian localities (Moscardón and Ricla). These two outcrops are separated 130 km but correspond to similar middle-outer platform domain (see Figure 1).

The Bajocian succession outcropping around the Moscardón village includes a set of buildups, up to 20 m thick and about 100 m wide. They are irregularly distributed (i.e., from closely to openly spaced) within a 10–15 km-wide facies belt, developed between inner (peritidal carbonates) and more outer platform environments (ammonite rich marly-dominated facies; Giner and Barnolas, 1980). The buildups have half-dome geometry and up to 30° inclined slopes. The overall geometry results from the stacking of successive lenticular or planar thrombolitic beds, with individual thickness up to 2–4 m, separated by dm-thick marly and bioclastic packstone beds. These thrombolitic beds correspond to successive high-frequency sequences, bounded by sedimentary interruptions. The buildups end with a sharp hardground, indicating a significant interruption of the sedimentation. The overlying marly-dominated outer platform successions are onlapping and filling the intermediate depressions between the buildups. Shallow platform bioclastic-oolitic packstones-grainstones eventually prograded over this leveled-off surface.

A discrete level with some small size bioherms (i.e., microbial-sponge patches 1–2 m thick, including some branching corals) is found at the onset of the progradational facies set in Moscardón. Age-equivalent and similar small-scale patches (1–2 m thick and 1–4 m wide) are present in the more northern outcrops of Ricla. These are irregularly distributed across successive discrete levels, located in the upper part of high-frequency shallowing and thickening upward sequences (Bersán and Aurell, 1997). The small bioherms in Ricla were also developed on top of an outer platform marly-dominated succession, in the lower part of a progradational facies belt, dominated by grain-supported peloidal and skeletal facies.

The differences in the geometry of the studied buildups are mainly explained by the interaction of high-order sea level fluctuations within the long-term accommodation changes recorded at basin scale during the Bajocian. In the Iberian basin, the maximum transgressive peak of the Middle Jurassic occurred during the mid-Bajocian, in the upper Niortense chronozone (Aurell et al., 2003; Gómez and Goy, 2006). The large-scale lenticular buildups of Moscardón were developed below this transgressive peak (i.e., Humpriesianum–lower Niortense chronozones), during a stage of long-term sea level rise. In contrast, smaller-scale patches (i.e., upper level of Moscardon and Ricla, Garantiana chronozone) were developed during the stages of sea-level highstand. This stage of long-term decreasing accommodation gain constrained the vertical and lateral development of microbialites. Moreover, the highstand progradation involved an increase of sedimentary supply, not favorable for the microbialite development.
Figure 1. Left: Palaeogeography of the Iberian basin (NE Spain) during mid-Bajocian times (compiled from Aurell et al., 2003 and Gómez and Fernández-López, 2006); Right: Synthesis of the stratigraphy and main facies distribution of the two studied successions at Moscardón and Ricla.
Microbial-Mediated Dolomite from Abu Dhabi Coastal Sabkha Sediments as Analogue to the Mesozoic Dolomite of the Arabian Plate

Fadhil N. Sadooni\textsuperscript{1}, Christian J. Strohmenger\textsuperscript{2}

\textsuperscript{1}Environmental Studies Center, Qatar University, P. O. Box 2713, Doha, Qatar
\textsuperscript{2}Qatar Center for Coastal Research, ExxonMobil Research Qatar, Doha, Qatar

Genuine supratidal sabkha to intertidal microbial mat and lowermost intertidal to shallow-subtidal, lagoonal environments are widest and best developed approximately 80km southwest of Abu Dhabi City where they extend more than 15km inland to Pleistocene-Holocene dunes. Detailed petrographic studies using SEM coupled with energy-dispersive X-ray spectrometer (EDX) analysis and Raman spectroscopy have been conducted on cored and surface carbonate and evaporite sediments from these sediments (Fig. 1).

Figure 1: Location map showing the coastal sabkha west of Abu Dhabi. Red dots mark study locations

Significant amounts of dolomite were found within samples from palaeo-microbial mats as well as within samples representing different sub-environments of palaeo-lagoonal deposits. The dolomite is fine crystalline and displays authigenic spheroids composed of subhedral to euhedral dolomite rhombohedra. Dolomite mineralogy of both spheroids and rhombohedra is proven by energy-dispersive X-ray spectrometer (EDX) analyses. Using a scanning electron microscope equipped with a cryogenic preparation system, the fine-crystalline dolomite displays subhedral to euhedral dolomite rhombs embedded in an organic matrix of extrapolymeric substances (EPS). XRD analyses and SEM photomicrographs comparing dolomite spheroids from sub-surface (approximately 6,000 to 900 uncalibrated \textsuperscript{14}C yr BP) and surface (Recent) microbial mats show the same XRD spectra and spherical morphologies. The dolomite is interpreted to have precipitated as a consequence of mineral nucleation and growth within the extracellular polymeric substances (EPS) constituting the microbial mats. Furthermore, it is postulated that also the authigenic dolomite identified within the different lagoonal deposits is of microbial origin.

Dolomite is also found to form in small semi-closed pores or “micro-niches” within the carbonate sediments. Typical “micro-niches” include skeletal grains chambers (Fig. 2), angles between mineral plates and local dissolution depressions. These “micro-niches” retains connate water for longer periods compared to the rest of the sediments; the water becomes anoxic due to the decay of organic materials (such as decomposed dead organisms) by microbial activity and hence causes the precipitation of dolomite. The later spread of dolomite...
would depend on the presence of well-connected networks of such pores. This concept means that microbial dolomite is not restricted to the lagoonal-sabkha settings and can be found in any depositional environment at any scale because most of carbonate sediments have high porosities upon deposition.

![Image](image_url)

**Figure 2**: A typical micro-niche formed of foraminifera chamber filled with dolomite

Microbial-mediated dolomite is interpreted to play a major role in the dolomitization process observed in arid climate carbonate reservoirs like the Permo-Triassic Khuff Formation, the Triassic Kurra Chine Formation, and the Jurassic Arab Formation. These reservoirs show early diagenetic dolomite clearly linked to facies successions dominated by intertidal, microbial-laminated carbonates; often encased by salina-type and sabkha-type anhydrite-after-gypsum layers.
Modern and Ancient Microbial Carbonates in Utah, U.S.A.: Examples from Great Salt Lake and the Uinta Basin’s Tertiary (Eocene) Green River Formation

Thomas C. Chidsey, Jr.¹, David E. Eby², Michael D. Vanden Berg³

¹Utah Geological Survey, Salt Lake City, Utah; ²Eby Petrography & Consulting, Inc., Denver, Colorado; ³Utah Geological Survey, Salt Lake City, Utah

Recent discoveries in Early Cretaceous microbialites in the deepwater offshore of Brazil (pre-salt Santos Basin reservoirs) as well as other large oil deposits in microbialites reveal the global scale and economic importance of these distinctive carbonates. Evaluation of the various microbial fabrics and facies, associated petrophysical properties, diagenesis, and bounding surfaces is critical to understanding these reservoirs. Utah is unique in that representative modern and ancient outcrop analogues of microbial reservoirs are present: the modern Great Salt Lake deposits, and the Tertiary (Eocene) lacustrine, Green River Formation from the Uinta Basin of eastern Utah.

Great Salt Lake is a modern hypersaline lake and a remnant of freshwater Pleistocene Lake Bonneville. It serves as a modern analogue to the Green River Formation and microbial lacustrine formations worldwide. Actively forming microbial stromatolites, pustular thrombolites, and tufa deposits are found within the lake and along its shores. Open constructional pores are common and often lined with acicular radial cements. Beaches and nearby dunes consist of abundant associated hypersaline ooids, coated grains, peloids, and rip-up clasts.

The Uinta Basin is a major depositional and structural basin that subsided during the early Cenozoic along the southern flank of the Uinta Mountains. Freshwater lakes developed between the eroding Sevier highlands to the west and the rising Laramide-age uplifts to the north, east, and south. The Green River Formation, comprising as much as 2000 m of sedimentary strata, accumulated in and around ancient Lake Uinta. Three major depositional Green River facies are associated with lake sedimentation: alluvial, marginal lacustrine, and open lacustrine. The open lacustrine environment is represented by nearshore and offshore shales and mud-supported carbonates, including microbialites – stromatolites, thrombolites, and oncolites.

Outcrops of the Green River Formation in the eastern part of the Uinta Basin display many of the features, both vertically and horizontally, observed in and around Great Salt Lake and in highly productive non-marine microbial and related reservoir facies worldwide. Thrombolitic heads contain large open constructional pores. Well-developed laminations in stromatolitic heads have abundant primary porosity between microbial filaments. Pisoids, ooids, oncoids, ostracods, and peloids are frequently associated with the microbial facies.

Michael D. Vanden Berg¹, David E. Eby², Thomas C. Chidsey, Jr³, Michael D. Laine (retired)⁴,

¹Utah Geological Survey, Salt Lake City, Utah; ²Eby Petrography & Consulting, Inc., Denver, Colorado; ³Utah Geological Survey, Salt Lake City, Utah ⁴Utah Geological Survey, Salt Lake City, Utah

In addition to microbial carbonates abundantly represented in cores from Carboniferous, Permian, and Jurassic marine reservoirs in various Utah oil fields, spectacular examples of microbial carbonates are also found in cores of lacustrine rocks from the Tertiary (Eocene) Green River Formation, Uinta Basin of northeastern Utah. These Green River cores serve as analogues for highly productive non-marine microbial and related reservoir facies worldwide, especially where cores are not available.

Green River cores reveal a variety of microbial facies and related fabrics. The overall cored section consists of medium gray siltstone and mudstone to light brown dolomitic mudstone with dark brown clay-rich and organic-rich zones. Interbedded with siltstone and organic-rich dolomitic mudstone are well-developed, porous microbial laminae and stromatolites. Grainstones composed of ooids, coated grains, pisoids, and peloids often overlie the microbialites. Soft-sediment deformation, bioturbation, and rip-up clasts are also often associated with these intervals. The grainstones and microbialites exhibit excellent storage consisting of microintercrystalline, interparticle, and moldic pore types. The newly acquired Skyline 16 Green River research core exhibits (1) low-relief stromatolites and thrombolites, (2) excellent primary mega- and microporosity within microbial fabrics, (3) porous dolomite, (4) grainstone (oolites, pisolites, peloidal grainstones, and skeletal material) with abundant interparticle and intraparticle porosity, and (5) sharp contacts between grainstones and microbialites.

Utah’s West Willow Creek field produces oil from a microbial mound interval (E2 carbonate bed), which pinches out up structural dip, within the Green River Formation—the only discovered conventional microbialite oil field in the Uinta Basin. Carbonate fabrics observed in core include stromatolitic and thrombolitic boundstones and rudstones, with associated grainstones composed of limestone or dolomite. Microbialite heads often consist of stromatolitic or thrombolitic crusts with well-preserved primary pore types. Stromatolitic and thrombolitic microbialites contain well-preserved primary interparticle and intraparticle porosity. Associated grainstones between laminated microbial fabrics are composed of peloids, ooids, and ostracods, which provide good to excellent interparticle porosity. Oncolites are also a significant component of the microbial system and contain microporosity along and around microtubules within oncid cortex layers.
Some lithifying microbial mats produce laminated accretionary structures (stromatolites) that are commonly found in the geological record. Sedimentological and biogeochemical studies of modern stromatolites are of key importance for interpreting past metabolisms and paleoenvironments of their ancient counterparts, which are today considered among the oldest evidence for the existence of life on Earth. This study investigates modern stromatolites from Lagoa Salgada (Brazil) using “clumped” isotope methodology and associated biomarkers to delineate paleoenvironmental conditions, and radiocarbon ($^{14}$C) dating to determine growth rates. By combing these data with macroscopic and microscopic sedimentological analyses it has been possible to define three major distinctive phases of stromatolitic laminae formation.

Figure 1 summarizes all the data. The initial phase began about 2300 yr. ago in a water body open to the ocean with a strong terrestrial influence, as indicated by distinctive biomarkers trapped as intracrystalline organic matter within the stromatolite laminae. Cementation under marine isotopic conditions was the dominant process stabilizing dolomite and quartz grains. Between 1980 and 1130 yr. ago, the stromatolites record a transitional phase wherein the water had an increased meteoric signal but $\delta^{13}$C values became strongly enriched (+11 to +17 ‰ PDB). The final phase, dated between 592 and 200 yr. ago, represents a fully microbial influenced system with Mg-calcite, Ca-dolomite and authigenic clays precipitating to form microbialite laminae with very positive $\delta^{13}$C values and predominantly meteoric $\delta^{18}$O values. Formation temperatures inferred from clumped isotopes measurements range between 23 and 37$^\circ$C, with values that systematically increase towards to the top of each phase. The overall growth rate occurring at Earth’s surface condition is 1 cm/100 yr. This result helps in estimating the formation rate of stromatolitic successions present in the geologic record.
Fig. 1. Mineralogy, carbon and oxygen-isotope, paleo-temperature, paleo-water, BIT index and relative sea level profiles of six facies from Lagoa Salgada stromatolite.
Microbial Carbonates in Space and Time

Quaternary and Modern Continental Microbial Deposits in the Iberian Range (NE Spain): Possible Analogues of Fluid Reservoirs


Fluvial tufas and associated carbonate deposits are widespread through the Quaternary record and very often the related tufa-depositing systems are still active at present (Ford and Pedley, 1996). Although their preservation potential is low and diminishes through time, thick and extensive deposits can also be found in Cenozoic and Mesozoic successions (Pentecost, 2005; Arenas-Abad et al., 2010). The geometrical and textural attributes of these deposits make them suitable for hosting fluids, and thus should be considered in studies of analogues of oil and gas reservoirs. Microbial facies (e.g., stromatolites, oncolites and boundstones of coated stems) can be significant components of these deposits, but other related facies (e.g., boundstones of bryophytes) also show participation of microbial communities.

In the Iberian Range, Quaternary tufa and associated deposits constitute thick and extensive outcrops. The studied deposits (Añamaza, Mesa, Piedra and Ebrón valleys) mostly developed during MIS 7, 7-6, 5 and 1, but also during MIS 9 and 6 (Peña et al., in press). In general, these formed in stepped fluvial systems of variable slope fed mainly by Mesozoic carbonate-rock aquifers, as it occurs nowadays, as a result of alternating stages of valley filling and erosional processes, which produced successive build-ups along the main and secondary valleys. These build-ups are composite lenticular and wedge-shaped bodies that open downstream (Fig. 1A), with lenticular (channel-like) transverse sections. Thickness of build-ups is up to 90 m, and their extent approximately 1 km long and several hundred metres wide.

A wide array of sedimentary facies make these deposits: stromatolites (Ls), boundstones of bryophytes (Lbr) and of other macrophyte stems (Lst), rudstones of phytoclasts (Lph) and of oncoids (Lo), mudstones to packstones of bioclasts and intraclasts (Lb), marls (M) and carbonate, mainly bioclastic, sands and silts (Sb). All these facies show high intergranular and framework porosity, as well as voids of decayed organisms, in particular Lbr and Lst. Some cavities can be partially or totally filled with microspar and spar calcite cements, but interconnected porosity commonly remains high. Fine to coarse alluvial facies are minor components, the latter related to erosional periods.

Within a build-up, the thickest, downstream deposits correspond mainly to facies Ls, Lbr and Lst, with a progradational-aggradational clinoform pattern made of highly inclined to vertical strata (Fig. 1A, B). The thinner, upstream deposits are dominated by mostly horizontal and slightly inclined strata with facies Lb, Sb, Lph, M and minor Ls and Lo. Transverse sections show chiefly irregular and discontinuous bodies. Geophysical facies are expected to show similar configurations, with greater continuity in longitudinal sections than in transverse ones.

Microbial laminated facies (Ls, Lo and Lst) (Fig. 1C) consist of undulate and irregular, alternating light (microspar-rich) and dark (micrite-rich) calcite laminae, up to 2-3 mm thick. Mostly filamentous bodies subperpendicular to the accumulation surface (bush- and fan-shaped bodies) make up the light laminae. In SEM images these bodies appear as empty tubes that evoke cyanobacterial templates (Fig. 1D).

Periodic monitoring of present-day fluvial tufa systems in the Iberian Range, based on hydrochemical and sedimentological parameters measured seasonally over 3 to 13 years, show that locally sedimentation rates can be as high as 1.6 cm/year. However, the rate values are highly variable depending on the depositional settings and hydrochemical composition (Vázquez-Urbez et al., 2010, 2011; Auqué et al., in press). The highest rates are recorded by laminated microbial deposits (Ls) and spongy moss-bearing boundstones (Lbr), whereas much lower rates correspond to sandy and silty deposits (Sb). During deposition, stromatolites experience much less erosion than the other facies, and thus are expected to have greater preservation potential in the geological record (Arenas et al., in press).
Figure 1. Quaternary fluvial tufas in the Iberian Range. A: Composite wedge-shaped body. B: Progradational-aggradational strata (facies Ls, Lbr and Lst). C: Stromatolite and minor phytoclastic deposits in a build-up. D: Bush-like bodies of calcite tubes formed from cyanobacteria (facies Ls).

Correlation of Depositional Microbial Microfabric Texture, Diagenetic Events and Petrophysical Properties of Upper Jurassic Smackover Formation Thrombolites

Sandra N. Tonietto\textsuperscript{1,2}, Michael C. Pope\textsuperscript{2}

\textsuperscript{1}Petrobras \textsuperscript{2}Texas A&M University

Microbial framework affects the primary porosity characteristics of the rock, which in turn influences the diagenetic modifications depending on pore geometry and connectivity. The primary porosity and permeability facilitates or hinders pore water circulation inside the bioherm. In peloidal microbial carbonate, the amount of peloids, the arrangement of the peloids in clusters, and the presence of framework cements (cements precipitated around the peloids in the microbial environment) compose the depositional framework. The water circulation in the interstitial space also can be influenced by the energy of the depositional environment. On the edges of bioherms the influence of environmental water usually are greater than in the center, where pore systems are more isolated. Consequently, the pore water chemistry near the center of the bioherm can be very different from the pore water chemistry near the bioherm edges. Microbial-mediated processes of oxic respiration, sulfate reduction, and methanogenesis are important in reef structures, and can change the chemical characteristics of the interstitial water, mainly in isolated portions of the reef (Morse and MacKenzie 1990). The interstitial water chemistry characteristics will drive carbonate cementation or carbonate dissolution, and also can modify the petrophysical attributes of the rock. Some reefs record varying alteration all the way to the centers, but some reefs only record alterations in their margins. These diagenetic differences between reefs most likely reflects environmental variations, such as differing wave energy and tidal range.

The Upper Jurassic Smackover Formation microbial carbonate reservoir in Little Cedar Creek Field, Alabama, USA, is approximately 12 km long, 1 to 3 km wide and from 1 to 19 m thick. Petrophysical characteristics are highly variable laterally and vertically inside this thrombolitic bioherm. Porosity values vary from 3 to 21%, and permeability can vary from 0.3 to 800 md, locally being as high as 2.5 darcys. The thickness of the thrombolite increases from northwest (protected side) to southeast (greater paleoenvironmental energy). Dissolution processes affected the thickest thrombolite areas more, and as a result the size of the pores varies laterally in the bioherm, increasing from mesopores near the northwest border to megapores near the southeast border, where dissolution produced vugs up to 6 cm diameter.

To determine the cause of lateral and vertical heterogeneities of this reservoir the relationship between the original framework texture and the subsequent diagenetic alteration of the thrombolitic carbonate was analyzed. Cements previously recognized in the thrombolitic reservoir are: fibrous-bladed rimming calcitic cement and fine mosaic intergranular calcitic cement produced during of marine diagenesis, whereas large mosaic calcite and anhydrite cements were produced during late diagenesis (Heydari and Baria, 2005). Previous diagenetic studies in this field were based only on petrography, and the lateral and vertical distribution of cements and dolomite was not determined. The cements were characterized using plain light petrography, cathodoluminescence, major and trace elements (using microprobe) and stable isotopes. Image analysis and petrophysical analysis (porosity, permeability and capillary pressure) were done and integrated with diagénesis data to construct a paragenetic sequence, characterize the pore system, and determine the impact of each diagenetic event on the geometry of the pore system.

The thrombolite depositional grains are mainly peloids, with minor amounts of skeletal fragments (benthic foraminifera, mollusk and equinoid). The grains are bounded by a syn-depositional or early diagenetic calcitic cement, which have the same dull luminescence as the grains, interpreted as being precipitated in the microbial environment. The next cementation phase is the calcitic bladed to drusy fringe, rimming the constructed microbial voids, lowering porosity and permeability. A compaction event followed producing stylolites.
dissolution event enhanced primary depositional porosity. Next, diagenetic blocky calcite cement and anhydrite cement were precipitated in both primary and secondary porosity. Late dolomitization occurred only in the southern portion of the field, and it greatly enhanced both porosity and permeability. Locally some dolomite is partially dissolved, indicating a second dissolution event.

The early bladed / drusy calcite cementation phase occurs across the entire thrombolite reservoir, with uniform cathodoluminescence, indicating pore water chemistry during that time was uniform. However the distribution of the late blocky calcite cement and dolomite are heterogeneous. Dolomite is restricted to the southwest portion of the reservoir, where blocky calcite occurs only in small amounts. The northeast portion of the reservoir has abundant blocky calcite cementation and local recrystallization of the calcite, but no dolomite. As the reservoir dips southwest, this heterogeneous cement distribution indicates that the deeper portion had a different pore water chemistry than the shallower, northeast portion of the reservoir.
Microbialites in Neogene-Quaternary Basins of the Betic Cordillera (Southern Spain): Potential Outcropping Analogues for Tufaceous Reservoirs

S. Pla-Pueyo¹, F. García-García², L. M. Nieto², C. Viseras³, I. Candy¹, S. Henares³, J. M. Soria⁴, J. E. Tent-Manclús⁴, J. Fernández³

SEDREGROUP: Sedimentary Reservoirs Workgroup.
¹Dpt. Geography, Royal Holloway University of London, TW20 0EX, Egham, Surrey (UK).
²Dpto de Geología, Universidad de Jaén, Campus Las Lagunillas s/n, 23071 Jaén (Spain).

Continental microbialites are abundant in Neogene and Quaternary sequences in southern Spain, but so far they have received very little intensive research. Tufas and travertines are particularly abundant in the Neogene-Quaternary extensional basins of this region but, with a few exceptions (e.g. Martin-Algarra et al., 2003; Garcia-Garcia et al., 2013), they have received very little attention. In this region, the abundance of exposed tufaceous sediment sequences, the richness of microbial facies and the quality of their preservation makes these examples significant as case studies for outcropping analogues for hydrocarbon reservoirs.

We present two examples of Quaternary tufa outcrops, one from the Guadix Basin and the other one from the Alcalá Basin (both in the centre of the Betic Cordillera of southern Spain). A facies model and a palaeoenvironmental interpretation, based on sedimentology and stable isotopic analysis, have been proposed for both of these outcrops. Whilst a review of tufas from elsewhere within the Betic Cordillera is presented to place these two sites into their regional context.

The example from the Guadix Basin is located in an area known as Rambla Becerra, and although the whole area is rich in tufaceous carbonates, and also presents hot-spring related travertines, we have focused only on a tufa build-up interpreted as a barrage tufa (Pla-Pueyo et al., 2009). The most abundant facies are coated stems and oncoids, and some stromatolitic facies either in the form of cascade facies or as domes in the area. These are interpreted as reflecting facies forming in association with the buttresses of the barrage and the ponds that have developed behind them.

The second example deals with a tufa complex developed in the area of Frailes (Alcalá Basin) involving carbonate precipitation in association with the interaction between a fluvial axial system and a transverse perched spring (García-García et al., 2013). Different facies associations can be recognised in relation to the fluvial system, ranging from purely detrital gravels to oncoidal limestones and stromatolitic domes forming a barrage or developing within a lacustrine pre-barrage area. The facies related to the perched-spring show mostly carbonate-coated curtains formed in association with hanging plants and cascade-related stromatolites. The presence of megaoncoids is related to a later stage of deposition, after the erosion of the previous tufaceous sediments.

Further porosity analysis of the facies outcropping in the two examples presented here, plus the detailed sedimentological and petrological study of other examples known from the Betic Cordillera will allow the potential of Neogene-Quaternary tufas as analogues for tufaceous reservoirs to be better established.

Acknowledgments

The research has been funded by Project CGL2009-07830/BTE, and the Working Groups RNM-200JA and RNM-369JA. The first author is currently enjoying a postdoctoral contract awarded by the Leverhulme Trust Foundation.
Burlington House
Fire Safety Information

If you hear the Alarm

Alarm Bells are situated throughout the building and will ring continuously for an evacuation. Do not stop to collect your personal belongings. Leave the building via the nearest and safest exit or the exit that you are advised to by the Fire Marshall on that floor.

Fire Exits from the Geological Society Conference Rooms

Lower Library:
   Exit via Piccadilly entrance or main reception entrance.

Lecture Theatre
   Exit at front of theatre (by screen) onto Courtyard or via side door out to Piccadilly entrance or via the doors that link to the Lower Library and to the main reception entrance.

Piccadilly Entrance
   Straight out door and walk around to the Courtyard or via the main reception entrance.

Close the doors when leaving a room. **DO NOT SWITCH OFF THE LIGHTS.**

Assemble in the Courtyard in front of the Royal Academy, outside the Royal Astronomical Society.

Please do not re-enter the building except when you are advised that it is safe to do so by the Fire Brigade.

First Aid

All accidents should be reported to Reception and First Aid assistance will be provided if necessary.

Facilities

The ladies toilets are situated in the basement at the bottom of the staircase outside the Lecture Theatre.

The Gents toilets are situated on the ground floor in the corridor leading to the Arthur Holmes Room.

The cloakroom is located along the corridor to the Arthur Holmes Room.
Ground Floor Plan of the Geological Society, Burlington House, Piccadilly