Introduction: AAPG Hedberg Research Conference on Microbial Carbonate Reservoir Characterization—Conference summary and selected papers

Ernest A. Mancini, William A. Morgan, Paul M. (Mitch) Harris, and William C. Parcell

INTRODUCTION

With the recent discovery of hydrocarbons in microbial carbonate reservoir facies along the South Atlantic margins, industry is keen to further the understanding of the origin and development of non-marine (lacustrine) to marine microbial carbonates, the nature of the depositional and diagenetic characteristics of microbialite and associated facies, and the sedimentary and petrophysical properties of microbial carbonate petroleum reservoirs. In this regard, the authors of AAPG Getting Started Series 19, *Microbial Carbonate Reservoirs*, Mancini et al. (2010), found that a vast literature on microbes and their functions in geological processes and products ranging from biogeochemistry to geomicrobiology, sedimentary petrology, and stratigraphy was available; however, only a small part of this literature deals with microbial carbonates as petroleum reservoirs. Further, these authors reported that sparse available literature exists on microbial carbonate reservoirs formed in lacustrine and continental settings and on carbonate reservoirs of abiotic origin in general.

To help address these shortcomings, an AAPG Hedberg Research Conference was proposed to focus on microbial carbonate reservoir characterization with an emphasis on depositional settings of microbial and abiotic carbonate reservoirs, especially in lacustrine settings associated with rift basins. The proposal was accepted August 21, 2010, and the Hedberg Conference was held in Houston, Texas, last June 3–8, 2012, with 85 attendees from 10 countries. The conference was dedicated to Wayne M. Ahr, who passed away in November 2011. He was one of the conference organizers, one of the intended field-trip leaders, and a friend to many at the conference.

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AUTHORS

Ernest A. Mancini ~ *Berg-Hughes Center for Petroleum and Sedimentary Systems and Department of Geology and Geophysics, Texas A&M University, College Station, Texas; emancini@as.ua.edu*

Ernest A. Mancini is professor emeritus in petroleum geology and stratigraphy in the Department of Geological Sciences, University of Alabama. He is the founding director of the Berg-Hughes Center for Petroleum and Sedimentary Systems, Texas A&M University, and served as state geologist and oil and gas supervisor for Alabama and director of the Geological Survey of Alabama.

William A. Morgan ~ *ConocoPhillips, Houston, Texas; present address: Morgan Geoscience Consulting, LLC, Houston, Texas; wamorgan24@gmail.com*

William A. Morgan is a consultant with 35 years of petroleum exploration, development, and research experience. His work has involved Cambrian through Tertiary carbonate reservoir successions in most of the carbonate provinces of the world. He is a past president of the SEPM (Society for Sedimentary Geology).

Paul M. (Mitch) Harris ~ *Chevron Energy Technology Company, San Ramon, California; MitchHarris@chevron.com*

Paul M. (Mitch) Harris is a senior research consultant and Chevron fellow with Chevron Energy Technology Company. His career's work has centered on facies-related, stratigraphic, and diagenetic problems that pertain to carbonate reservoirs and exploration plays in most carbonate basins worldwide. He is a past president of the SEPM (Society for Sedimentary Geology).

William C. Parcell ~ *Department of Geology, Wichita State University, Wichita, Kansas; william.parcell@wichita.edu*

William C. Parcell is an associate professor in the Department of Geology at Wichita State University. His research focus is on sedimentary basin analysis, stratigraphic modeling, and reservoir characterization.

OVERVIEW OF MICROBIAL CARBONATES

The following overview of microbial carbonates is modified from sections 1 and 2 of AAPG Getting Started Series 19, *Microbial Carbonate Reservoirs* (Mancini et al., 2010).

Microbes are defined as microorganisms visible only under a microscope. Some examples are bacteria, fungi, molds, algae, and protozoa. Unlike the older classification of living organisms that included kingdoms of animals and plants, classification of living organisms today places all life forms into three main branches or domains of life—Bacteria, Archaea, and Eukarya (Konhauser, 2007). Bacteria (including cyanobacteria) and Eukarya (including red and green algae and fungi) are involved in the formation and diagenesis of microbial carbonates. We follow Wood (1999) and Kenter et al. (2005) in defining microbial carbonates (also called microbialites or microbolites) as precipitates formed in situ directly or indirectly by the physiological activity of benthic microorganisms. Burne and Moore (1987) have described microbialites as organosedimentary deposits formed as a result of the interaction between benthic microbial communities and detrital or chemical sediments.

Microbial carbonates have a variety of textures and fabrics, some of which may be specific to certain microbes and recognizable if those microbes have good potential for preservation, e.g., *Girvanella*, *Renalcis*, and *Epiphyton*, or if they have specific metabolic processes that leave distinctive geochemical signatures. Most importantly, for microbial carbonate reservoir porosity and permeability, certain microbial textures and fabrics—the building blocks of microbial carbonates—determine the nature of depositional porosity in microbial carbonate reservoirs. The building blocks—microscale features—can also be paleoenvironmental indicators. Examples of building blocks include peloids of various sizes (the largest of which could be called “clots”), “shrubs” (arborescent growth forms), filaments (called skeletal calcimicrobes such as *Girvanella*, *Epiphyton*, and *Renalcis*), spherulites, and arguably, radiaxial fibrous calcite cements. These building blocks—depositional microfabrics—are commonly recognizable in thin section if they have not been obliterated by diagenesis.

Larger structures, comprising building blocks in the aggregate, are recognizable to the unaided eye in hand specimens, cores, and even image logs. Remember that these macrostructures are composed of one or more microfabrics. Different depositional microfabrics—building blocks—may represent differences in the original depositional environments and in the responses to the environments by the endemic microbial biota. Most importantly, they represent the initial depositional pore and pore-throat geometry that will either be preserved or altered by diagenesis to form the ultimate petrophysical characteristics of microbialite reservoirs. Microbial macrostructures include stromatolites, thrombolites, dendrolites, leiolites, and laminates. According to Aitken (1967), Kennard and James (1986), and Braga et al. (1995), stromatolites are laminated organosedimentary structures, thrombolites lack lamination and are characterized by a mesoscopic clotted fabric, dendrolites are arborescent growth forms, and leiolites are dense undifferentiated microbial boundstone. Laminates are generally laminated, organic-rich carbonate mudstone.

Some workers argue that nonmarine tufas and travertines, together with Precambrian deposits interpreted to have formed abiotically, should not be included as microbialites. However, Chafetz and Folk (1984) provided convincing evidence that bacterial activity was a primary factor in the formation of nonmarine travertine deposits in Italy, and tufas and travertines, particularly travertines with their shrub microfabrics, generally fall in the category of microbialites, according to most workers. As most current literature indicates, however, we generally still lack an ability to distinguish what truly is and what is not microbial or what is organic or inorganic in origin; therefore, ambiguity remains as far as how broad the term microbialites will eventually be.

CONFERENCE PROGRAM

To assess and advance the state of our knowledge of microbial carbonate reservoirs, the Hedberg Research Conference program included presentations on the depositional processes affecting the origin, development, distribution, continuity, and preservation of potential microbial petroleum reservoir facies; postdepositional processes controlling the enhancement, occlusion, and preservation of porosity and permeability in microbial reservoirs; and depositional and postdepositional factors influencing the heterogeneity, connectivity, quality, and productivity of microbial carbonate reservoirs.

Table 1 lists the conference sessions, presentations, and authors. The abstracts for the presentations are posted as an AAPG Search and Discovery article (Mancini et al., 2012).

The following are summaries of the sessions and the core workshop and field trip held in association with the conference, with an emphasis on some of the key learnings.

OVERVIEW OF MICROBIALITES

The overview session of the conference comprised five papers dealing with modern microbial systems and recognition of microbial vs. nonmarine systems (Table 1). Harris et al. examined microbialites, travertines, and tufas in modern rift settings as potential analogs for hydrocarbon reservoirs, grouping the settings into early rift, other lacustrine, and marginal marine settings, and using remote sensing techniques to characterize their distribution. Their study documents the wide array of carbonate facies, their complexity, and their location in various rift settings. Baskin et al. noted a variety of growth forms in the microbialite bioherms in the Great Salt Lake of Utah, ranging from large columnar forms, tens of meters in diameter and height, to meter-scale forms. Stromatolites in the Great Salt Lake favor depositional highs, whether tectonic or paleodepositional, and their distribution is controlled by salinity and depth-related factors. Reid et al. characterized stromatolites of the Bahamas, where robust stromatolites live in open-marine conditions in a variety of settings typically associated with migrating ooid sands. Although trapping and binding are important components of stromatolite accretion, carbonate precipitation via microbial activity is also critical to microbial growth and preservation. The famous stromatolitic and thrombolitic mounds of Hamelin Pool, Shark Bay, Australia, were described by Jahnert and Collins. Microbialites began growing in the pool approximately 2000 yr ago in response to progressive restriction of the embayment that resulted in higher salinity, higher alkalinity, and higher evaporation. Although the substrate has a gentle gradient, a distinct depth zonation to the microbial communities exists. Della Porta et al. investigated the characteristics of abiotic and microbially mediated fabrics and porosity in nonmarine carbonates. They described the wide range of depositional settings, from suabaerial to subaqueous, and the associated diversity of resultant fabrics. A variety of settings yield potential reservoir facies with complex pore geometries, but the controls on pore systems in these diverse systems are not well understood.

GEOBIOLOGY AND GEOCHEMISTRY OF MICROBIALITES

This session of the conference consisted of five presentations focusing on characterization of microbes in carbonates in a variety of depositional and diagenetic settings (Table 1). Diaz et al. investigated the function of different microbial communities on carbonate platforms in the Bahamas and Caicos. Extracts of DNA were used to identify microbial communities in higher-energy, low-energy, and mat-stabilized environments. Early findings suggested that a high diversity of microbial forms is present across many phyla regardless of the energy of the system, in contrast to previous studies that suggested that turbulent hydrodynamic conditions resulted in lower bacterial abundance, lower nutrient levels, and lower overall microbial diversity in marine sands. Piggot et al. investigated the interstitial water chemistry, sediment chemistry, and bacterial community profiles from carbonate mudbanks in Florida Bay to determine bacterial community changes with depth along geochemical gradients and with mineralogy. Microbial communities are stratified along geochemical gradients and clustered within diagenetic zones at two of three mudbanks studied and, thus, may be indicators of conditions promoting early diagenesis. Roberts et al. and Kenward et al. (2013, this issue) described their successful laboratory precipitation of ordered dolomite in the presence of Archaeal methanogens and cells. No dolomite formed in the absence of Archael biomass or in the presence of bacterial biomass. Their work suggests that dolomite precipitation is controlled by the surface character of microbial cells or other organic carbon in the system. Pederson et al. described oncolites with a wide range of nuclei (intraclasts, mollusk fragments, etc.) from beds capping the uplifted Maré Atoll in the Loyalty Islands of New Caledonia. Carbon and oxygen isotope data from the rinds of the oncolites show a progressive trend from marine to freshwater influence, suggesting implications for porosity; creation of the microbial rinds in these oncolites inhibit moldic porosity creation, unlike those of ooids. Hickson et al. documented thick successions up to 200 m (656 ft) of microbial carbonates that can be traced for up to 25 km (15.5 mi) in the Oligocene—Miocene Horse Spring Formation of southern Nevada. Exposures allow characterization of microbial facies from marginal to basinal positions, with domal fabrics being common up dip and laminar fabrics more common in basinal settings. In addition, basinal carbonates show more negative carbon and oxygen isotope values compared with their more proximal basin-margin equivalents, providing additional criteria for distinguishing between microbial environments. In a special invited presentation, Fairchild et al. reported on their project to produce an atlas of Brazilian microbialites.

Table 1. Technical Program for the AAPG Hedberg Research Conference on Microbial Carbonate Reservoir Characterization (June 3–8, 2012, Norris Conference Center, Houston, Texas)

Date	Title	Authors
Overview of Microbialites (Oral Session)		
Cochairs: P. Reid and K. Verwer		
June 4, 2012	Analogs for Carbonate Deposition (Microbialites, Tufas, and Travertines) in Early Rift Setting	Paul Harris*, James Ellis, and Samuel J. Purkis
	Microbialite Bioherms in Great Salt Lake, Utah: Influence of Active Tectonics and Anthropogenic Effects	Robert Baskin*, V. Paul Wright, Neal Driscoll, Graham Kent, and George Hepner
	Lessons Learned from Modern Marine Stromatolites, Bahamas	R. Pamela Reid*, Miriam S. Andres, Emily M. Bowlin, Kelly L. Jackson, and Erica C. Parke
	Characteristics, Distribution, and Morphogenesis of Microbial Carbonate Systems in Shark Bay, Australia	Ricardo J. Jahnert* and Lindsay B. Collins
	Nonmarine Carbonates: Microbially Mediated vs. Abiotic Fabrics and Porosity	Giovanna Della Porta*, Federica Barilaro, and Enrico Capezzuoli
Microbial Carbonate Reservoirs, Reservoir Analogs, and Geologic Models I (Poster Session)		
Cochairs: M. Aurell and E. Franseen		
June 4, 2012	Outcrop and Subsurface Characterization of Microbialite Facies in the Ordovician Arbuckle Group of Missouri and Kansas	Chamandika Warusavitharana*, William C. Parcell, and Evan Franseen
	Microbial Mound in Tuscumbia Limestone, Subsurface Walker County, Alabama	David Kopaska-Merkel*, Steven D. Mann, and Jack C. Pashin
	High-Relief Microbial Boundstone Platforms	Giovanna Della Porta*, Ted Playton, Nereo Preto, Jeroen A.M. Kenter, Juan R. Bahamonde, Oscar Merino Tome, and Paul Harris
	Evidence for the Microbial Origin of the Tengiz Unit I Boundstone Slopes (Precaspian Basin, The Republic of Kazakhstan)	Miriam S. Andres, Tomaso R.R. Bontongnali, Jeroen M. Kenter*, Paul Harris*, Crisogono Vasconcelos, Judith A. McKenzie, Ruslan Manakhayev, and Steve D. Jenkins
	Mesozoic, Synrift, Nonmarine, Microbialites from the Wessex Basin, United Kingdom	Dan Bosence
	Coral-Microbial Buildup Development in an Upper Jurassic Carbonate Ramp (Kimmeridgian, Sierra de Albarracín, Spain)	Marc Aurell*, Beatriz Bádenas, and Gato San Miguel
	Lacustrine Microbial Carbonate Facies in Core from the Lower Cretaceous Toca Formation, Block 0, Offshore Angola	Matthew S. Wasson*, Arthur Saller, Miriam Andres, Daniel Self, and Anthony Lomando
Group Discussion of Presentations for the Day		
Comoderators—P. Reid, K. Verwer, M. Aurell and E. Franseen		
Microbial Carbonate Reservoir Core Workshop		
Cochairs: P. M. Harris and W. Morgan		
June 5, 2012	The Microbial-Dominated Reef and Slope of the Capitan Margin	Paul Harris
	The Microbial-Dominated Slopes of Tengiz Field, Precaspian Basin, Kazakhstan	Jeroen A. M. Kenter*, Paul Harris, and Joel F. Collins

Table 1. Continued

Date	Title	Authors
	Microbially Influenced Waulsortian Mounds in the Lower Mississippian (Tournasian) Lodgepole Formation, Dickinson Field Complex, Williston Basin, North Dakota	William A. Morgan*, Ray Mitchell, and Wayne M. Ahr
	Characteristics and Modeling of Upper Jurassic Smackover Microbial Carbonate Buildups, Facies, and Reservoirs in the Northeastern Gulf of Mexico	Ernest A. Mancini*, Wayne M. Ahr, William C. Parcell, and Grayson Ridgway
	Late Jurassic Microbialite Reservoirs of Southwestern Alabama, Little Cedar Creek Field: A Core Presentation	Lawrence R. Baria* and Ezat Heydari
Microbial Carbonate Reservoirs, Reservoir Analogs, and Geologic Models II (Oral Session)		
Cochairs: S. Bachtel and S. Guidry		
June 6, 2012	Seismic Geomorphology of Microbial-Dominated Margin and Slope Environments around an Isolated Platform, Tengiz Field, Kazakhstan	Steven L. Bachtel*, Henry Posamentier, Ted E. Playton, Steve Jenkins, Elrad Iskakov, Zhanibek Katrenov, and Paul Harris
	The Sequence-Stratigraphic and Paleoclimatic Controls on Microbial Carbonates of the Carbonate-Evaporite Dominated Late Carboniferous (Moscovian) Paradox Basin, Southeastern Utah	Gary L. Gianniny*, Daniel J. Powers, Shannon M. Boesch, Amanda A. Peterson, and Jordan Van Sickle
	Calcisponge-Microbialite Reef Facies, Middle Permian (Guadalupian), Northwest Shelf-Margin of Permian Basin, New Mexico, USA	Gregory P. Wahlman*, David M. Orchard, and Govert J. Buijs
	Microbialites in Zechstein Cycle 2 Carbonates (NE England and Poland): Types and Source Rock Perspectives	Mirosław Słowakiewicz* and Maurice E. Tucker
	Pre- and Post-salt Nonmarine Carbonates of the Namibe Basin, Angola	Ian Sharp, Klaas Verwer*, Hercinda Ferreira, Marco Snidero, Vladimir Machado, Erik Holtar, Roger Swart, Julian Marsh, Laurent Gindre, Cai Puigdefabregas, and Morten Fejerskov
	Large Lacustrine Microbialite Bioherms from the Eocene Green River Formation: Stratigraphic Architecture, Sequence-Stratigraphic Relations, and Depositional Model	H. Paul Buchheim*, Stanley M. Awramik, V. Leroy Leggitt, Timothy M. Demko, Kathryn Lamb-Wozniak, and Kevin M. Bohacs
Microbial Carbonate Reservoirs, Reservoir Analogs, and Geologic Models III (Poster Session)		
Cochairs: W. Parcell and G. Wahlman		
June 6, 2012	The Carbonate Mud Mounds of the Lower Cretaceous Cupido Formation: An Unusual Occurrence of Microbial-Dominated Carbonate Buildups Cropping Out Remarkably in NE Mexico	Gustavo Murillo-Muñetón* and Steven L. Dorobek
	Outcrop Analog of Pre-salt Microbial Series from South Atlantic: The Yacoraite Formation Salta Rift System (NW Argentina)	Youri Hamon*, Sébastien Rohais, Rémy Deschamps, and Marta Gasparrini
	Salta Basin, Argentina: A Good Analog for Phanerozoic Lacustrine Microbialite-Bearing Reservoirs	Gerson J. S. Terra*, Eduardo B. Rodrigues, Ednilson B. Freire, Ricardo Lykawka, Guilherme P. Raja Gabaglia, Roberto M. Hernández, and Juan I. Hernández
	Lacustrine Carbonates–Facies Evolution, Diagenesis: Eocene Green River Formation, Piceance Creek Basin, Colorado	J. Frederick Sarg, S. Huang, K. Tanavsuu-Milkeviciene*, and J. Feng

Table 1. Continued

Date	Title	Authors
	Controls on High-Frequency Oolite-Microbialite-Coral Reef Sequences, Upper Miocene, SE Spain	Robert H. Goldstein*, Evan K. Franseen, and Christopher J. Lipinski
	The ExxonMobil Lacustrine Collaborative: Idaho Hot Springs Limestone as an Analog Addressing Lacustrine Carbonate Reservoir Presence and Quality	Kathryn Lamb-Wozniak*, Kevin M. Bohacs, Timothy M. Demko, Stephen Kaczmarek, Catherine Lash, David M. Cleveland, Jason Eleson, Matt Fabijanic, Orla M. McLaughlin, and Stacie L. Gibbins
Group Discussion of Presentations for the Day		
Comoderators—S. Bachtel, S. Guidry, W. Parcell and G. Wahlman		
Geobiology and Geochemistry of Microbialites (Oral Session)		
Cochairs: G. Della Porta and T. Fairchild		
June 7, 2012	Microbial Characterization of Carbonate Surface Sediments from the Bahamas and Turks and Caicos Platforms	Mara R. Diaz, Alan M. Piggot, and James S. Klaus*
	Microbial and Geochemical Characterization of Carbonate Mudbanks from Florida Bay	Alan M. Piggot*, James S. Klaus, and Peter K. Swart
	Low-Temperature Dolomite Formation: Microbes and Other Mechanisms	Jennifer A. Roberts*, Paul A. Kenward, David A. Fowle, Robert H. Goldstein, Luis A. González, and David S. Moore
	Composition, Distribution, and Diagenesis of Microbial Oncolite Beds Capping the Uplifted Atoll of Maré, Loyalty Islands, New Caledonia	Chelsea Pederson*, Donald F. McNeill, and James S. Klaus
	Lateral Variation in Microbial Carbonate Facies and Stable Isotope Geochemistry at Multiple Scales in the Oligo-Miocene Horse Spring Formation of Southern Nevada	Thomas A. Hickson*, Jessica A. Kopp, and Melissa A. Lamb
Special Invited Presentation		
Chair: Sylvia M. Couto Anjos		
June 7, 2012	An Atlas of Brazilian Microbialites	Thomas Fairchild*, Dimas Dias-Brito, Rosemarie Rohn, and Paulo Tibana
Characterization and Modeling of Microbial Reservoirs I (Poster Session)		
Cochairs: D. Bosence and E. Heydari		
June 7, 2012	Self-Sculpting Bahamian Microbialite	Robert N. Ginsburg*, Gregorio Aranea, and Katarzyna A. Kulpa
	Pore Structure, Porosity, and Permeability of Continental Carbonates: A Case Study of Pleistocene Travertine (Southern Tuscany, Italy)	Federica Barilaro, Klaas Verwer, Fabio Lapponi, and Giovanna Della Porta*
	Three-Dimensional Pore Connectivity Evaluation in a Holocene Microbialite Head	Marcelo F. Rezende*, Sandra Nélis Tonietto and Michael C. Pope
	Pore Type Characterization and Petrophysical Properties on Microbial Carbonate Reservoirs	Sandra N. Tonietto*, Emily K. Shane, Wayne M. Ahr, and Michael C. Pope
	Workflow for Reservoir Characterization, Formation Evaluation, and 3D Geologic Modeling of the Upper Jurassic Smackover Microbial Carbonate Reservoir Facies at Little Cedar Creek Field, Northeastern Gulf of Mexico	Sharbel Al Haddad* and Ernest Mancini
	Simulation of the Upper Jurassic Smackover Carbonate Facies at Little Cedar Creek Field, Northeastern Gulf of Mexico	Moetaz Mostafa

Table 1. Continued

Date	Title	Authors
	Reservoir Analog Model for Oolite-Microbialite Sequences, Miocene Terminal Carbonate Complex, Spain	Christopher J. Lipinski*, Evan K. Franseen, and Robert H. Goldstein
Group Discussion of Presentations for the Day		
Comoderators—G. Della Porta, T. Fairchild, D. Bosence, and E. Heydari		
Characterization and Modeling of Microbial Reservoirs II (Oral Session)		
Cochairs: G. Eberli and H. Chafetz		
June 8, 2012	The Role of Microbial Activity on Petrophysical Properties	Gregor P. Eberli*, Klaas Verwer, Giovanna Della Porta, and Ralf J. Weger
	Travertine Macro- and Microporosity	Henry Chafetz
	Carbonate Rock-Forming Processes in the Pre-salt "Sag" Successions of Campos Basin, Offshore Brazil: Evidence for Seasonal, Dominantly Abiotic Carbonate Precipitation, Substrate Controls, and Broader Geologic Implications	Steve Dorobek*, Leo Piccoli, Brian Coffey, and Aaron Adams
Group Discussion and Summary of the Conference		
E. Mancini, W. Morgan, W. Parcell, and P. M. Harris		

*Presenter.

MICROBIAL CARBONATE RESERVOIRS, RESERVOIR ANALOGS, AND GEOLOGIC MODELS

These oral and poster sessions included 19 articles on Paleozoic to Miocene deposits in marine and nonmarine settings (Table 1). Seven of these presentations are published as articles in this volume: Lamb-Wozniak et al. as Bohacs et al. (2013); Goldstein et al. (2013); Kopaska-Merkel et al. (2013); Sarg et al. (2013); Słowakiewicz and Tucker as Słowakiewicz et al. (2013); Wahlman et al. (2013); and Warusavitharana et al. as Warusavitharana and Parcell (2013).

The main finding from these sessions is that microbial and abiotic carbonate facies can be found globally in Precambrian to Holocene strata in nonmarine and in shallow- to deep-water marine environments. Eight of the presenters in these sessions discussed lacustrine and continental microbial carbonate facies. Wasson et al. studied core from the Lower Cretaceous Toca Formation from offshore Angola and determined that the carbonate reservoir facies was lacustrine and consisted of fossiliferous grainstones to wackestones with microbially mediated oncoids, ooids, and peloids, and stromatolitic and dendritic boundstones similar to those occurring today in East African rift basins. The other presentations focusing on lacustrine and nonmarine deposits examined possible analogs for the microbial or abiotic carbonate reservoirs recently discovered in the South Atlantic. These articles included descriptions of carbonates from Eocene and Miocene lake deposits in the western interior of the United States (Lamb-Wozniak et al.; Bohacs et al., 2013, this issue; Buchheim et al.; Sarg et al.; Sarg et al., 2013, this issue), from Upper Cretaceous lake deposits from Argentina (Hamon et al. and Terra et al.), from Lower Cretaceous lake deposits from onshore Angola (Sharp et al.), and from Upper Jurassic nonmarine deposits from England (Bosence).

For marine settings, presentations included Paleozoic and Mesozoic examples of carbonate platforms with high-relief, steep depositional slopes and margins (Andres et al.; Bachtel et al.; Della Porta et al.; Wahlman et al., 2012, 2013, this issue), Upper Jurassic and Lower Cretaceous examples of carbonate ramps (Aurell et al.; Murillo-Muñeton and Dorobek); and examples of Paleozoic and Miocene carbonate shelves and platforms (Gianniny et al.; Goldstein et al., 2013, this issue; Kopaska-Merkel et al., 2013, this issue; Słowakiewicz and Tucker; Słowakiewicz et al., 2013, this issue; Warusavitharana et al.; Warusavitharana and Parcell, 2013, this issue). The common characteristics of geometry, facies belts, and lithofacies types of high-relief microbial boundstone platforms were summarized by Della Porta et al. Aurell et al. described an excellent reservoir analog for microbial carbonate buildups, and reservoirs developed on a low-angle carbonate ramp. Outcrops in northeast

Spain provide a continuous and extensive exposure of an upper Kimmeridgian carbonate ramp succession in depositional dip and strike directions. According to Goldstein et al. (2013, this issue), a significant Miocene carbonate shelf succession of oolite, microbialite, and coralgal reefs deposited in association with glacioeustasy and evaporitic drawdown is well exposed in southeast Spain. Stromatolites were the initial transgressive lithofacies in the four stratigraphic sequences, and thrombolites were the later transgressive deposits observed in these sequences.

CHARACTERIZATION AND MODELING OF MICROBIAL RESERVOIRS

Ten presentations focused on petrophysical properties and flow characteristics of microbial carbonate reservoirs in these sessions (Table 1). Four of these articles are included in this special issue of the *AAPG Bulletin*: Al Haddad and Mancini (2013), Chafetz (2013), Lipinski et al. (2013), and Rezende et al. (2013).

The main finding from these sessions is that microbial and abiotic carbonate precipitates can have excellent hydrocarbon reservoir potential. Microbial carbonate rocks (stromatolites) have high depositional interparticle and intraframe porosity and permeability resulting from microbially induced cementation and growth that act to build a strong framework that resists compaction and preserves primary porosity (Eberli et al.). Rezende et al. (2013, this issue) found that different microbial textures result in differing pore systems. Holocene thrombolites with a chaotic fabric have a complex pore geometry and high pore-network connectivity. Planar stromatolites with a horizontal fabric have a simple pore geometry and low pore-network connectivity, and digitate stromatolites with a vertical fabric have a simple pore geometry and medium to low network connectivity. The genetic classification of carbonate porosity of Ahr (2008) has potential to serve as a means to classify porosity in microbial carbonate reservoirs (Tonietto et al.). Ginsburg et al. focused on the various morphologies that occur in living Bahamian microbialites in an attempt to better understand environmental parameters and processes that influence them.

The presenters in these sessions also demonstrated that further understanding of travertine is crucial in the exploration for and development of carbonate reservoirs in rift basins. According to Dorobek et al., abiotic precipitation of different carbonate phases and cementation formed important lacustrine reservoir framestone fabrics (shrublike features) in the Campos Basin, offshore Brazil. However, Chafetz (2013, this issue) stated that bacteria are responsible for the precipitation and accumulation of travertine deposits. He explained that bacteria induce precipitation of carbonate minerals on the cell walls and then become entombed in a second generation of abiotically precipitated spar cement that envelopes the bacterially induced constituents and the initial carbonate precipitate. Microporosity is an associated product of this process where the decay of eubacteria in the rock results in unconnected submicrometer- to micrometer-size porosity. These pores are found in bacterially induced shrubs, peloids, and oncoids. Microporosity is common, along with other bacterially related pore types, such as shelter, interparticle, and those associated with rafts and foam rock, in travertines. Barilaro et al. studied pore structure, porosity, and permeability of Pleistocene–Holocene travertines from southern Italy and found that they have heterogeneous growth fabrics and pore structures as a result of biotic and abiotic processes and subsequent diagenesis. The fabrics identified were shrub, crystalline crust, stromatolitic, raft, wavy sheet, coated grain, bubble, and reed; and porosity types included primary porosity (interdendritic, bubble, interlaminar, shelter, and intraskeletal) and secondary porosity (biomoldic, vuggy, and fracture). Porosity and permeability are highly variable and are mainly controlled by fabric orientation and amount of cementation.

Modeling of microbial carbonate and associated reservoir facies and the inherent flow units was shown to be a complex endeavor by the presenters in these sessions. A static three-dimensional (3-D) reservoir analog model for Miocene oolite-microbialite sequences as seen in outcrop in southeastern Spain was constructed by Lipinski et al. (2013, this issue). This modeling demonstrated that the vuggy, thrombolitic boundstone facies was a flow unit characterized by significant thickness, significant lateral extent, and large storage capacity resulting from high pore volume, good permeability, and good lateral continuity. In contrast, the stromatolitic and dense, thrombolitic boundstone facies were found to act as baffles to flow and were characterized by variable lateral extent and less storage capacity because of low pore volume, low permeability, and limited connectivity. Al Haddad and Mancini (2013, this issue) performed 3-D geologic reservoir modeling for the Upper Jurassic microbial carbonate and associated reservoir facies at the Little Cedar Creek field, southwest Alabama. The microbial carbonate reservoir is composed of boundstone associated with thrombolitic buildups. These buildups developed in clusters in the field, and the clusters are separated by interbuildup areas characterized by a thick section of microbially influenced lime mudstone and wackestone. Porosity in the microbial reservoirs includes depositionally constructed void (intraframe), diagenetic solution-enhanced void, and vuggy pore types. The pore system in the buildups provides for high permeability and connectivity. However, interbuildup areas are characterized by a thick section of low permeability to nonreservoir rock that serves as a potential baffle or barrier to flow. Moetaz conducted reservoir simulation on these microbial and associated reservoirs at Little Cedar Creek field.

PRECONFERENCE FIELD TRIP

To further enhance the conference program, a preconference field trip was held on Upper Cambrian microbial carbonates of central Texas. The field trip, led by Andre W. Droxler of Rice University and William A. Morgan of ConocoPhillips, on June 1–3, 2012, focused on stromatolitic and thrombolitic depositional fabrics, textures, and facies in the Upper Cambrian Point Peak and San Saba Members of the Wilberns Formation as exposed along the Llano and San Saba Rivers, central Texas. In addition to stromatolites and thrombolites, calcimicrobes such as *Epiphyton* and *Renalcis* are also present, as are extensive grainstones, some of which are interspersed between heads of microbialites. These deposits are part of the Sauk III supersequence that formed an extensive carbonate platform on the Laurentian paleocontinent. The microbialites include extensive biostromal as well as exceptionally well-exposed biohermal forms. One of the key reservoir-related aspects of the trip was the observation that small bioherms of 1 m (3 ft) in diameter or less aggregate into progressively larger accumulations and complexes that, locally, extend for hundreds of meters. A better understanding of scaling patterns of potential microbial reservoir facies would be important for reservoir-simulation models.

CORE WORKSHOP

An important component of the conference program was the core workshop. This workshop highlighted five case studies showing different characteristics of microbial carbonate reservoirs and analogs. Two of them (the Capitan margin of the Permian Basin and Tengiz field in Kazakhstan) are examples where microbialites occur at the margin and along the steep slopes of high-relief marine shelves and platforms. Harris summarized detailed studies of the microbially dominated reef and slope of the Capitan margin in the Permian Basin that were done on the unique set of cores and logs obtained from the Gulf PDB-04 research well. Because of the highly prograding nature of the margin, these cores captured a complete succession of shelf-to-basin facies similar to those found in outcrops to the west (e.g., Permian reef geology trail at McKittrick Canyon). The slope and reef facies of the Capitan Formation in the core reflect the varied carbonates that formed at the seaward edge of this shelf margin; debris primarily from the reef and upper slope accumulated on the slope as beds of skeletal dolowackestones to dolograinstones and as blocks of doloboundstone. The slope grades upward in the core into the reef, reflected in a change from allochthonous doloboundstone to in-situ doloboundstone, in turn reflecting a reef framework of sponges and microbial carbonate, and the filling of growth framework and vuggy porosity by marine cement, internal reef-derived sediments, and locally, siltstone. Kenter et al. presented seismic, core, and log data from the Tengiz field, Pricaspian Basin of Kazakhstan. Platform backstepping through the late Visean resulted in approximately 800 m (2625 ft) of relief above a Famennian platform, followed in the late Visean to Serpukhovian by up to 2 km (1.2 mi) of progradation of a microbially dominated margin and slope. Cores and formation microimage (FMI) logs show the in-situ microbial boundstone to be 150–200 m (492–656 ft) thick, with textures that include relatively featureless micritic to peloidal fabrics, or irregular laminar fabrics and amalgamated semiconcentric laminar masses. The Tengiz studies suggest that (1) microbial-boundstone production extended to approximately 300 m (984 ft) water depth; (2) carbonate production on the slope was controlled by environmental parameters (temperature, nutrients, and oxygenation), which may be directly or indirectly related to water depth, but the microbial boundstone response to relative sea level changes differed from modern reefs; (3) progradation can occur at high rates despite the lack of platform-top shedding (slope vs. highstand shedding); and (4) concepts of leeward progradational vs. windward aggradational margins do not directly apply.

The other three examples presented at the core workshop—one Waulsortian mound example from the Williston Basin and two examples from the Smackover

Formation of the Gulf Coast—show variability of microbial deposition in marine ramp settings. Morgan et al. described Waulsortian mounds mainly of fenestrate bryozoan cementstones and peloidal mudstones from the Tournasian Lodgepole Formation in the Dickinson field complex, Williston Basin in North Dakota. Centimeter-scale stromatactis vugs that may contribute significantly to total reservoir porosity are characteristic of the mounds. The microbial signature within the mounds is in the form of small peloids that commonly form a clotted texture and are endemic to the mounds, in contrast to larger peloids found locally within the mounds and in coeval, off-mound sediments. The Dickinson mounds appear to have nucleated on a subtle paleohigh that was situated some 80 km (50 mi) basinward of the toe of slope, grew below wave base, and exhibit neither shallowing-upward trends nor evidence of subaerial exposure. Circular and loaf-shaped mound complexes, as large as 2300 × 7500 m (7546 × 24,606 ft), can be identified on 3-D seismic data, but the typically 100-m (328-ft)-thick individual mounds are too thin for details to be seismically imaged; consequently, detailed well-log correlations are necessary to identify their stratigraphy in the subsurface. Mancini et al. described shallow-water microbial buildups developed on paleohighs and antecedent depositional topography within an inner carbonate ramp of the Upper Jurassic Smackover Formation in the northeastern Gulf of Mexico. These microbialites included calcimicrobes, red algae, foraminifera, sponges, echinoids, and bivalves and attained a thickness of 58 m (190 ft). Although the principal control on reservoir architecture and geographic distribution of Smackover reservoirs is the fabric and texture of the depositional facies, diagenesis (mainly dissolution and dolomitization) is a significant factor that preserves and enhances reservoir quality. The higher reservoir quality and productivity of the microbial boundstone is attributed to the higher permeability and greater interconnectivity of this facies because of the nature of the pore system (pore topology and geometry and pore-throat-size distribution) instead of the amount of porosity. Pore-throat-size distribution in the intercrystalline- and vuggy-dominated pore system of the dolomitized and leached boundstone is characterized by a higher percentage of large-size pores having larger pore throats. Baria and Heydari described Upper Jurassic microbialite facies from the Little Cedar Creek field in southwestern Alabama, which appear to extend as a continuous reservoir for at least 32 km (19.9 mi) and closely parallel the shoreline in the Late Jurassic near the mouth of a pronounced embayment. The width of this buildup ranges from 6.4 to 0.4 km (4 to 0.25 mi) in a dip direction and commonly measures up to 20 m (66 ft) in thickness. From a stratal perspective, the microbialite sits atop a transgressive sequence of laminated mudstones and bioturbated lime wackestones and packstones of a mid- to inner ramp setting. A varied assemblage of encrusting, columnar, and branching algal and cyanobacterial masses, serpulid worm tubes, foraminifera, bivalves, gastropods, and local sponges(?) is present. Because of early marine cementation (micrite and finely bladed calcite), the microbialite was commonly fractured during burial, and these nearly vertical fractures afford an additional aspect of reservoir continuity and hydrocarbon deliverability to the reservoir.

CONFERENCE OUTCOMES

The conveners' goals for the conference were to provide the opportunity for participants to interact and to (1) discuss the origin, development, distribution, and stratigraphic occurrence of microbialites, microbial carbonate buildups, and depositional characteristics of microbial carbonate reservoirs; (2) promote discussions on the formation, alteration, distribution, and preservation of porosity and permeability in microbial carbonate reservoirs; (3) identify strategies to further our understanding of microbial carbonate facies and reservoirs and the hydrocarbon productivity of these reservoirs; and (4) publish selected articles presented along with a summary of the results of the conference.

The oral and poster presentations and the many discussion sessions of the conference furthered our understanding of microbial carbonates and reservoirs in several directions and also pointed out very clearly the interplay of multiple factors leading to their initial formation, diagenesis, and resultant pore systems. The complexity of those interactions was captured on a whiteboard by Della Porta and Bosence (2012) during the summary discussion session at the end of the conference (Figure 1). The figure illustrates the broad spectrum of topics addressed at the conference as well as areas in need of further research.

In broad terms, based on the presentations and discussions at the conference, we conclude the following:

1. We have a reasonable understanding of the marine depositional settings where microbial carbonate facies, reservoirs, and buildups develop. This understanding

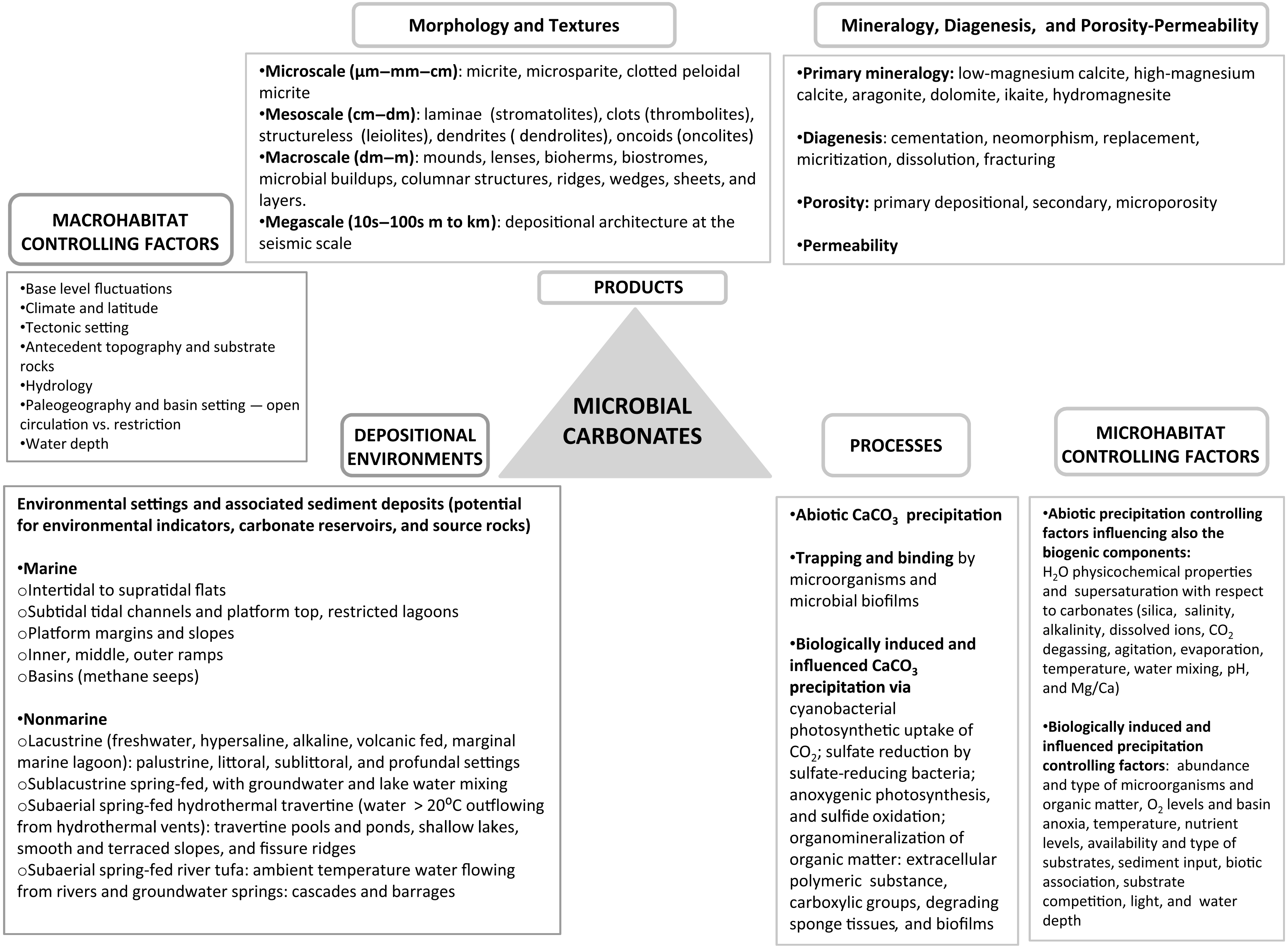

Figure 1. Summary of discussion session on microbial carbonates captured by Della Porta and Bosence (2012) at the Hedberg Research Conference on Microbial Carbonate Reservoir Characterization. The complexities of microbial carbonates are illustrated by the multiple factors that influence the growth, diagenesis and, ultimately, reservoir potential of these systems.

will help to formulate strategies related to the spatial distribution and geometry of microbial carbonate geobodies for exploration using seismic data and in reservoir development using 3-D reservoir modeling and simulation.
2. We still have much to learn regarding the nonmarine depositional settings, particularly lacustrine microbial facies in rift basin settings from the pore scale to the basin scale.
3. Clarifying the origin of travertines, tufas, and abiogenic carbonates requires additional physical, inorganic, and organic geochemical, biological, and isotopic studies.
4. We do not have a sufficient understanding of the relationship of marine and nonmarine microbial facies, textures, and fabrics to construct a reasonable classification for all microbial carbonates at this time.

Understanding the function of abiotic and biotic depositional and postdepositional processes is crucial to deciphering reservoir porosity and permeability systems and flow units in microbial carbonate reservoirs, thus improving the understanding of the characterization, modeling, and predictability of nonmarine (lacustrine) reservoir systems. Through the publication of the abstracts of the conference presentations as AAPG Search and Discovery Article 90153 (Mancini et al., 2012) and the publication of this special issue of the *AAPG Bulletin*, we begin to build a record that can be used to unravel very complicated geological-physical-geochemical-biological relationships apparently inherent to microbial carbonate facies and petroleum reservoirs.

Along these lines, this special issue of the *AAPG Bulletin* includes 12 articles that represent the spectrum of topics presented at the conference. Seven of these articles provide subsurface and outcrop examples of microbial carbonate facies and reservoirs in marine and lacustrine settings. These articles include Bohacs et al. (2013), Goldstein et al. (2013), Kopaska-Merkel et al. (2013), Sarg et al. (2013), Słowakiewicz et al. (2013), Wahlman et al. (2013), and Warusavitharana and Parcell (2013). The articles by Lipinski et al. (2013) and Al Haddad and Mancini (2013) emphasize characterization and 3-D modeling of microbial carbonate facies and reservoirs. The complexity of the petrophysical properties of microbialites is discussed in the Chafetz (2013) and Rezende et al. (2013) articles. Kenward et al. (2013) describe the factors controlling the precipitation of dolomite in the laboratory.

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