Controls on Facies Distribution and Architecture of Holocene Carbonates

Holocene systems offer the unique opportunity to explore, explicitly compare, and rigorously quantify and test process-response linkages in carbonate depositional systems and to explore and qualify map-view patterns in facies and granulometric attributes. Geochemical, physical, climate, nutrient, and biological controls can also be explored to enhance predictability in both marine and lacustrine systems. Examples of some current and pending projects include:
Comparative Morphometrics of Facies Patterns of Carbonate Isolated Platforms and Rimmed Shelves: Holocene, Southeast Asia

Gene Rankey

SUBSURFACE APPLICATION: Understanding and predicting facies distribution and sizes in carbonate isolated platforms and shelves, most directly related to Cenozoic systems of southeast Asia and the Middle East
STATUS: Part of project completed, project expansion planned
TIMING: Phase 1 results reported in 2016; expansion underway
FUNDING: Seeking additional funding

Objective and Relevance to Sponsors
Carbonate strata form important reservoirs in southeast Asia. Many of these systems represent Eocene-Miocene isolated platforms and rimmed shelves, in which reservoir quality is highest in depositional facies associated with coarse, reef-derived sand and gravel. Although seismic data from some of these systems illustrate platformward progradation of reef sand aprons, in most, such direct facies indicators are absent (e.g., Masaferro et al., 2003). In such scenarios, geological analogs can provide conceptual models and as raw data to predict facies dimensions, orientation, and configuration. Modern Southeast Asia carbonate systems have been interpreted to be grossly analogous to the region’s Cenozoic systems (e.g., Wilson, 2011), but the Holocene carbonates of this area have not been examined systematically. To fill this gap, the overall objectives of this study are to systematically examine and quantify spatial facies patterns of Holocene southeast Asia isolated platforms and rimmed shelves, and relate these patterns to controlling processes. Last year’s meeting presented final results from 27 isolated platforms of the South China Sea, and this year’s project expands on those insights by including 1) more geographic diversity and 2) rimmed shelves.

Background and Methods
Recent efforts (Rankey and Garza-Perez, 2012) focused on mapping spatial patterns of facies on isolated platforms using lower-resolution (25-30 m$^2$ pixel) Landsat data, and compared the spatial patterns to oceanographic processes. In addition to mapping and quantifying facies patterns at a higher level of detail (<2.5 m$^2$ pixels), this project built (and will continue to build) on that earlier project in three important ways: A) Mapping more platforms, and at a higher resolution, and expand to rimmed shelves; B) Expanding the range of “process space” to include more southeast Asian examples of more direct relevance to sponsors; and C) Examining the nature and rates of change on platforms. It will provides data that will be linked to the subsurface by construction of seismic models to explore the geophysical expression of different geological scenarios (see Duarte and Rankey proposal).

Phase One of this project included analysis of a suite of multi-temporal remote sensing images from 25 isolated platforms in South China Sea (Spratly and Paracel islands) (Figure 1). Phase Two will expand to include additional platforms and several rimmed shelves. For each area, QuickBird, WorldView or GeoEye 4-band multispectral remote
Remote sensing data (<2.4 m² pixels) over each platform provide the fundamental data. The data analysis includes:

1) Remote sensing data queried to derive thematic maps of spectral lithotopes, interpreted in the context of depositional facies/geomorphic elements. These maps were generated using a mix of unsupervised and supervised classification techniques (e.g., Figure 2A,B).

2) These thematic maps form the basis for the quantitative analysis of spatial patterns. Utilizing a GIS, the data were queried and characterized in terms of facies element composition (what is there), size (how big are they) and configuration (how are they spatially arranged), expressed in terms of probabilities (Figure 2C,D).

3) Multi-temporal data from several areas provide the foundation for analysis of change on these systems, with focus on reef sand aprons. Data from 2001-2004 (the oldest commercially available high-resolution remote sensing images) and 2012-2016 (“recent”) from the same platforms illustrate changes in spatial extent of facies (and human constructs), and simple numerical models quantify the nature and rates of change.

Deliverables
The primary results of the study to date include qualitative and quantitative analyses of facies patterns of South China Sea isolated carbonate platforms. The data were presented in 2016 at the sponsors meeting, are available presently on the KICC sponsors web page, and ultimately, will be expanded in final reports. Pending additional support, the project plan is to expand to other southeast Asia analogs, including other isolated platforms and rimmed shelves.

References


Figure 1. Map of general location of data analyzed to date. Data include a suite of platforms, in a range of settings, to attempt to sample the range of oceanographic and tectonic variability. Phase 2 will expand geographically and include rimmed shelves as well.

Figure 2. Representative facies attribute data from Pigeon Atoll (Spratly Chain). A) Uninterpreted remote sensing image; B) Thematic map of facies; C) Width of reef sand apron vs. orientation of the margin (direction the margin faces); Note the wide aprons of Northwest-facing margin; D) Plot showing the probability of occurrence of a given facies with distance from margin. The colors used correspond to the thematic map of facies in (B).
Microbes, Organic Matter, Initial Porosity, and Early Diagenesis of Holocene Lacustrine Deposits, Bahamas

Hannah Hubert and Gene Rankey

SUBSURFACE APPLICATION: Bahamian lacustrine systems provide a potential process analog to aspects of offshore Brazil and Angola pre-salt carbonate lacustrine reservoirs.
STATUS: Focused-term project in progress
TIMING: Significant results to be reported
FUNDING: Fully funded by SEPM, KU Geology, and KICC

Purpose
The discovery of hydrocarbon accumulations in pre-salt carbonate reservoirs of offshore Brazil and Angola have motivated the search for microbial lacustrine carbonate analogs that could provide understanding of reservoir genesis, heterogeneity, or volumetrics. Although previous efforts have mapped spatial patterns of extant large microbial lacustrine systems on a large scale (e.g., Harris et al., 2013), or have described general aspects of environments and facies models and the variability of microbial lacustrine systems (e.g., Gierlowski-Kordesch 2010; Wright, 2012), the details of the origins and controls on depositional textures and porosity are less well constrained. To address these unknowns, the goal of this study is to test two linked hypotheses: 1) the morphology, distribution, and growth fabrics of calcareous microbialites vary within and among Bahamian lakes as a function of organic matter and microbial consortia; and 2) growth fabrics are related to the pore size, pore distribution, and pore networks within calcareous microbialites. Ultimately, this study will assess the influences of organic matter, microbial consortia, and growth fabrics on initial porosity and permeability (phi/k) of carbonate accumulations in Holocene hypersaline lacustrine systems. Although growth fabrics (and phi/k) can modified by diagenesis, the depositional framework can influence ultimate reservoir quality, distribution, and continuity. As such, understanding the organic matter and microbial influences on growth fabrics and porosity of these different lacustrine systems is crucial to successful assessment and ultimate exploitation of the pre-salt reservoirs.

Project Description
The goal of this study is to assess the possible roles of several controls on the nature of lacustrine sedimentation and early cementation. To do so, the project will start by describing lakes from Crooked – Acklins Platform (CAP), Bahamas. Here, un lithified microbial mats and lithified microbialite heads are abundant and cover several km² of hypersaline lacustrine systems. Each lake is small (< 1 km²) shallow (< 1 m), likely receives inflow during wave events and/or through adjacent beach ridges, and is characterized by net evaporation. They include a surficial orange to green microbial mat, underlain by black, organic-rich, H₂S-rich laminated sediment. Shallow push cores suggest the lakes can include up to 1 m of sediment, much of which is dark and laminated. Some lakes include lithified bioherms up to 40 cm+ high and a meter across.
that can include spherules, botryoidal cement, and laminated micrite. To do so, this study includes study of Holocene/recent sediment, with specific objectives:

1. **Map spatial patterns in bottom type**, including morphology of surficial microbial mats. Preliminary results suggest a diversity of bottom types (including widespread microbial mats; lithified vs. granular bottom; isolated and amalgamated heads) in lakes. Additionally, whereas some lakes have no lithified surfaces, others have widespread hardgrounds. We expect that changes in bottom type within and among lakes relate to changes in depth and degree of connection to open-ocean conditions.

2. **Describe textures, sediment and cement in surface sediment and shallow cores**. Preliminary study of sediment and cement reveal probable abiotic textures, and some probable biotic (including microbial) fabrics, and TOC which ranges up to 25%. We expect that systematic CT, petrographic, SEM, mineralogic observations (and isotopic, and elemental analyses to be completed with additional funding, or in subsequent years) will reveal lateral changes in micro-and macro-fabrics within the lakes.

3. **Differentiate microbial consortia and variability in amount and type of organic matter within and among lakes and microbial morphotypes**. Preliminary study of shallow cores from one lake reveals an abundance of organic matter - TOC ranges up to 25%. Microbial indicator species identified by DNA or RNA analyses should emphasize which microbes covary with the character of microbialites and which do not. Microbes that correspond with changes in texture will then be studied to understand their potential role in creating textures and porosity in microbialites. GC/MS analyses of organic matter and DNA or RNA analyses of microbes in the two different lacustrine systems are expected to show that organic matter types and microbial consortia differ between lakes that are, and are not, forming microbialites.

4. **Characterize the porosity and pore distribution of Holocene microbialite heads and spherules**. Preliminary study of nuclear magnetic resonance (NMR) and X-ray computed tomography (CT) scan data in a lithified microbialite head reveal three zones with fabric differences in regards to geometry, connectivity, and associated porosity. The total porosity and the pore sizes, distribution, and connectivity in these zones will be evaluated quantitatively in several heads using the digital data.

5. **Compare macroscale and microscale textures, organic attributes, and porosity of microbialite heads**. The influence of textures on porosity will be explored to understand the relationship between rock textures (observed in SEM, thin section, slab, and CT) and depositional pore characteristics. We expect the depositional textures will have a unique relationship with the pore network characteristics such as pore geometry and connectivity, based on the attributes of microbialite size, packing, and framework fabric (Rezende et al., 2013). The rock fabric is expected to be related to pore size and connectivity, and ultimately back to the micro-organisms.

**Deliverables**

Collectively, the significance of this effort lies in developing an understanding of sedimentary textures, mineralogy, and fabrics of carbonate precipitates in Holocene coastal lacustrine systems, insights that can be used to understand ancient reservoir systems. This year will catalog and interpret the results of field mapping, sedimentologic observations, petrographic, SEM, CT-scan and geomicrobiological observations of lakes from CAP. Ultimately, the integrated observational approach – from the scale of SEM
study of µm-scale structures to spatial patterns in lakes – should provide a unique actualistic perspective on the original (e.g., pre-diagenetic) mineralogy, geochemistry, and fabrics of lacustrine systems.

References


Figure 1. A) Representative spherulite from surface sediment with a radial fabric and no visible nucleus. B) Competitive growth boundary (identified by red arrow) between spherules indicating they grow in situ. C) Shallow core from a coastal lake illustrating well developed laminated, organic-rich layers. D) Spherules embedded in organic matter from shallow push core.
Figure 2. A) Slab photograph of microbialite head showing laminated to thrombolitic to shrub-like appearance. B) Slab photograph of microbialite head with interpreted growth packages drawn. C) Laminations made of alternations of micrite and clear fibrous cement. D) Close association among organic matter, fibrous micritic carbonate, and porosity.
Comparative Ichnology of Holocene and Pleistocene Successions: The Role of Biota in Sediment Reworking

Steve Hasiotis, Gene Rankey, and Alexa Goers

SUBSURFACE APPLICATION: Carbonate reservoir rocks of late Paleozoic to Neogene in age in the oil and gas fields around the world, particularly of Jurassic and Cretaceous ages
STATUS: Phase 1 of this project; expanding on previous work
TIMING: 2 years; data being collected; student thesis research underway; results being reported as produced, thesis (two manuscripts) writing underway
FUNDING: Funded by KICC; opportunity for additional funding for spinoffs

Purpose
After deposition, carbonate sediment texture can be modified by the activity of organisms; these processes can either degrade or enhance porosity and permeability. Although descriptions of carbonate successions commonly refer to “burrows” or “bioturbation,” systematic descriptions and assessment of their possible effect on reservoir quality are few (Cunningham et al. 2009). To start to address this need and to understand the nature, extent, and controls on biomodification in carbonates, this study proposes a comparative analysis of ichnologic patterns between recent and Pleistocene carbonate, shallow shoreface successions, testing two linked hypotheses: 1) Ichnologic patterns (trace fossil type, density, depth) in Holocene and Pleistocene successions vary among environments (beach ridge, foreshore, upper shoreface, lower shoreface); and 2) Ichnologic patterns in each environment are similar in Holocene and Pleistocene examples.

Project Description
Our preliminary analysis of outcrops exposed on the western margin of Crooked Island and Long Cay (Crooked-Acklins Platform, southern Bahamas) revealed a Pleistocene reef, shoreface, and backshore succession. Grainstone bodies, the focus of this research, form well-defined shore-parallel ridges in plan view. These deposits include shallowing-upward successions, from upper shoreface to back-beach deposits with ubiquitous physical sedimentary structures, at scales from lateral accretion surfaces several m tall to trough cross-stratification to current and wave ripples. Akin to siliciclastic analogs, trace fossil diversity and abundance varies with the interplay of depositional energy, sedimentation rate, oxygenation, and salinity. Trace fossils in this carbonate succession can appear at a range of density, from isolated, individual traces to complete reworking of the stratal bedding and texture (Figure 1).

Pleistocene stratigraphy of Crooked Island and Long Cay are being described by measuring standard stratigraphic sections. We expect to describe 5-7 sections and encounter environments from reef, shoreface, to back-beach; sections will include descriptions of grain size, type, sorting, and physical sedimentary structures. We will characterize vertical and lateral changes in trace fossil associations as well. From these data, we will be able to place the trace fossils into the depositional framework. We will systematically collect ~50 samples for slab, thin section, CT-scan, and phi/k analysis.
To characterize the Holocene shoreline system, three transects will run normal to the shoreline offshore, but sampling density and design will focus on capturing the range of water depths and geomorphic variability. The subaqueous portion of each transect will be studied via SCUBA. At each location, the general sedimentologic and ecologic aspects of the seafloor will be described (for example, abundance of sea life, presence and distribution of burrowing organisms, physical sedimentary structures such as ripples). In the field, in situ observations will describe the type and size of traces. Across transects, as logistically possible given water depth and energy conditions, a representative suite of burrows will be cast in resin and/or in dental plaster to capture the architectural morphology and determine how it may produce macrochannels and macropores that are (or could) be later filled with different carbonate sediment types (and, potentially modified by diagenesis). Upon return from the field, burrow casts will be studied for their morphology and tortuosity in order to understand the number and depth of branching and, by proxy, the form and shape of macrochannels. Sediment samples collected from bioturbated intervals and areas vs. nonbioturbated intervals will be analyzed for differences in grain-size distribution, size, and sorting and facies relations. Sediment from burrow fills will be compared to the surrounding matrix to determine how burrow fills affect local porosity and permeability. All of these data on bioturbation patterns—field and lab analyses—will be tied to the sedimentary and geomorphic remote sensing images to build ichnocoenoses (trace communities) and ichnofacies models and define the relationship between grain size, facies, biogenically mediated porosity and permeability trends. Through this systematic analysis, we expect to find marked differences in grain size, sorting and type, and sedimentary structures and ichnology, both along and across depositional strike.

**Deliverables**

Although underappreciated in carbonates, trace fossils are important as they provide: 1) important clues to interpreting EODs, as well as syndepositional and postdepositional conditions; 2) information on how bioreworking impacts and modifies the original depositional fabric and texture; 3) biomodified textures commonly have different porosity and permeability than the primary depositional matrix. This phase 1 of this research will provide 1) a catalog of trace fossils, from Pleistocene and Holocene examples, 2) document the environments in which each occurs. These insights, and the assessment of the role of biota in sediment retexturing, will provide new conceptual models for the extent and significance of ichnology in the modification of depositional porosity with respect to geomorphic bodies.

**References**

**Figure 1.** Shallow marine trace fossils. A–B) Rosselia changing form to Cylindrichnus, indicating a change from a cohesive to shifting seafloor sediment. C) Conichnus, a resting trace of a sea anemone. D) Vertical Ophiomorpha, indicative of higher energy systems in which 1-2 m deep shafts dominate the upper parts of the burrow systems. E) Upper part of Cylindrichnus, indicating slower aggradation of the seafloor. F) Gastrochaenolites, Trypanites, and Entobia visible in cross section of early cemented carbonate seafloor ripped up and redeposited; note borings are found on all of the margins, indicating reworking of the clast.
Comparative Ichnology of Pleistocene, Holocene, and Modern Carbonate Shoreface Deposits: A Predictive Ichnofacies Model and Effect on Rock Properties

Alexa Goers, Steve Hasiotis, and Gene Rankey

SUBSURFACE APPLICATION: Understanding the influence of biota in modifying carbonate textures, porosity and permeability. Results should be broadly applicable, but most directly to shallow carbonate shoreface reservoirs, such as the Jurassic Smackover Formation or Jurassic of the Middle East.

STATUS: Focused-term project nearing completion

TIMING: Significant results available to membership this year

FUNDING: Partial from consortium

Purpose

Burrowing organisms can markedly alter depositional sedimentary textures, diagenesis, and petrophysical characteristics of carbonate strata. Although descriptions of carbonate successions commonly refer to bioturbation, quantitative data on spatial variability of ichnodiversity and ichnofabrics are rare (e.g., Goldring et al. 2005). Furthermore, few studies focus on the influence of biogenically modified sedimentary fabrics on reservoir quality (e.g., Pemberton & Gingras 2005; LaCroix et al. 2012). To address this issue, this study characterizes ichnologic and sedimentologic variability in Pleistocene, Holocene, and modern carbonate shoreface deposits. The purpose of this study is to evaluate trace fossil associations and ichnofabrics within carbonate shoreface environments to produce a conceptual ichnofacies model, and as a secondary goal, to explore the effect of bioturbation on permeability pathways and porosity.

Project Description

Comparative analyses of ichnologic and sedimentologic trends in Pleistocene, Holocene, and modern shoreface deposits provide quantitative information on the controls of trace fossil distribution and preservation in carbonate strata. Integration of field observations with spot-minipermeameter, petrographic, and image analysis data provide a means to assess the effect of burrowing organisms on carbonate depositional textures.

This study focuses on Pleistocene and Holocene outcrops and modern shoreface deposits on the western, leeward margin of Crooked Acklins Platform, southern Bahamas (CAP). CAP islands are composed of Pleistocene and Holocene reef, shoreface, and backshore deposits that form shore-parallel topographic ridges. The present-day shelf is 500–2,200 m wide, has an arcuate trend, and gently slopes (<0.5°) to a depth of up to 31 m before the drop off. CAP is influenced by southeasterly trade winds, yet storm-associated waves from the W–NW are the strongest hydrodynamic influence on the leeward margin.

Variability in Pleistocene, Holocene, and modern deposits is captured through integration of outcrop analyses with assessment of traces and sediments on the present-day shelf. Four transects on the extant seafloor record biota and traces with variability of bottom conditions, sediments, and geomorphic elements. Petrographic analyses quantify trace-
fossil influence on grain type, size, sorting, and cement type and abundance. Image analysis of photomicrographs provides point count data for grain constituents, cement abundance, and percentage of porosity.

Preliminary results illustrate that ancient and modern deposits show similar along-strike variations in grain type, size, and sorting, as well as degree of bioturbation, ichnodiversity, and burrow depth. Sedimentologic and ichnologic variability on the leeward margin of CAP are interpreted to reflect proximal-to-distal and along-strike variations of depositional energy. Preserved porosity of Pleistocene samples ranges from 2.5–27.9%, and permeabilities range from 0.023–220 Darcys. Petrographic analysis reveals that mm-scale horizontal burrows (e.g., *Planolites*) are characterized by greater porosity than the matrix, as burrow interiors have little to no internal cement. Spotminipermeameter data reveals that cementation patterns associated with biogenic modification of sedimentary fabrics can result in alteration of permeability by up to 2 orders of magnitude.

![Figure 1](image)

**Figure 1.** Representative traces of Pleistocene shoreface deposits in outcrop and thin section. A) Vertical, cement lined burrows in cross-stratified, moderately sorted, medium sand peloid-ooid-composite grainstone with ichnofabric index (ii) 4. B) Thin section photomicrograph of A, illustrating coarser, poorly sorted burrow fill with less internal cement than the matrix. C) Horizontal burrows in plane laminated, peloid-ooid-skeletal grainstone with fenestrae and ii 3. D) Thin section photomicrograph of C, illustrating coarse-fine laminae with blocky calcite cement, modified by mm-scale horizontal burrows. Note decreased cement in burrow interior. *Cy* = Cylindrichnus, *Op* = Ophiomorpha, *Pl* = Planolites.

**Deliverables**

This study examines the nature and distribution of trace fossils within carbonate shoreface strata to establish the relationship between ichnology, diagenetic processes, and
petrophysical characteristics. Results of this study will integrate trace-fossil associations of sedimentary facies with field and lab data to produce a conceptual ichnofacies model specific to carbonate shoreface systems. This model will aid in understanding and predicting the distribution and effects of biogenic modification on strata and porosity and permeability within similar ancient carbonate systems.

References
Integrated Field and Modeling Analysis of Oceanographic Controls on Sedimentology of Holocene Ramp Carbonates: Yucatan Shelf, Mexico

Thomas C. Neal, Gene Rankey, and Christian M. Appendini

SUBSURFACE APPLICATION: Many carbonate reservoirs represent deposition in ramp settings, including the Permian San Andres and Grayburg formations, Permian Basin, Jurassic Hanifa and Arab formations, Middle East, Jurassic - Cretaceous strata of north Atlantic and GOM. This system is a “mixed heterozoan-photozoan” system as well, and can provide insights into Cenozoic Caribbean and SE Asia analogs.

STATUS: Part of a long-term project in progress

TIMING: Project will be completed with significant results reported at 2017 meeting

FUNDING: Full from KICC, GSA, SEPM and AAPG

Purpose

Many ancient carbonates ramp deposits are prolific hydrocarbon reservoirs. Although sequence stratigraphy of such successions is well-documented, the complex processes controlling sedimentologic variability are less well understood (Wright and Burchette, 1998), in part due to the paucity of modern analogs. To develop more rigorous predictive conceptual models for the sedimentation and dynamics of carbonate ramps, this study characterizes the Holocene northeast Yucatan ramp system to enhance understanding sedimentary dynamics of carbonate ramp systems. It specifically tests the hypotheses that hydrodynamics and bathymetry directly influence sediment characteristics (size, sorting and type) and geomorphology of carbonate ramps. Understanding hydrodynamics and carbonate sedimentology of ramps are important for constructing depositional models of variability within analogous ancient ramps.

Project Description

The study area (Figure 1A) lies on the northeastern coast of the Yucatan peninsula. Located in the tropics along the southern Gulf of Mexico, the broad marine ramp dips gently and extends northward out to 245 km from the long (350 km) and low-lying coastline system of beaches, lagoons and barrier islands (Appendini et al., 2012). Siliciclastics are rare in the region and the ramp is covered by sheets of carbonate sand with widely scattered reefs (Logan, 1969). Geomorphic elements within the study area include the Isla de Holbox, a long (30 km) and narrow (1.5 to 3 km) barrier island, with near- and off-shore areas of the gently dipping homoclinal Yucatan ramp to the north, and the Laguna de Yalahau, a large (300 km²) protected muddy lagoon to the south (Figure 1B).

To explore the hypothesis, this study integrates remote sensing, field, petrographical and granulometrical observations of surficial modern sediments with climate data, oceanographic observations and hydrodynamic modeling. To test the hypothesis, this project focuses on several specific objectives. First, the area will be mapped using remote sensing data with Landsat and RapidEye satellite imagery, and a bathymetric survey acquired during field work provides detailed geomorphic and bathymetric information of the research area, and the spatial context for all sampling and subsequent modeling. Second, nearly 200 surficial sediments samples from nine onshore to offshore
transects were collected and the petrographic and granulometric analyses conducted describing the type and quantifying grain size, sorting, composition, and abundance. Next, the physical oceanographic and metrological conditions are characterized using in-situ tide, wave and current measurements and regional data. A variety of regional climate data sources were utilized along with hydrodynamic measurements from two Acoustic Doppler Current Profiler (ADCP) meters (during the mid-February to mid-March 2014 field study period). This information also provides the basis to analyze the effect of a range of oceanographic processes (tide, wave and current) on sediment transport using DHI’s M-21 two-dimensional hydrodynamic modeling software. All these results will then be used to integrate sedimentology and hydrodynamic modeling results within a GIS framework. This analysis will explicitly compare spatial variability in sedimentology, geomorphic elements, and hydrodynamics to explore potential linkages.

It is probable that no other ramp in the geologic record was exactly like the modern Yucatan. Therefore, using the insights from the modern as a starting point, the final objective is to explore potential geological variances by numerically modeling a suite of conceptual models with different geomorphologies and key input parameters (e.g. wind direction, waves, regional currents and tidal ranges). This step enables the isolation and analyses of the variables to assess their specific and combined influence upon the system across a spectrum of ramp settings.

**Deliverables**

This study supports the broader multi-year project re-examining a classic ramp system that has not been systematically explored in more than 40 years. Specifically, this study details the sedimentology, climate, and bathymetry of the Holocene ramp system of northeastern Yucatan, as well as demonstrates variations of sediment composition and accumulation by geomorphic element. Hydrodynamic modeling results link specific controls (wind, waves, currents, tides and bathymetry) on sediment transport and deposition within the various geomorphic elements in this system. Creating and modeling a series of conceptual models, with different characteristics and parameters than those of the Yucatan ramp system, provides insights into the controls on sedimentologic variability for a greater number of ramp systems, including those in the rock record. This study supports the collective efforts of the larger project generating data and insights for conceptual models for heterogeneity in ramp analogs and examining broader changes and oceanographic controls on across- and along-strike variability. Understanding the variability in sedimentologic and the hydrodynamic conditions and their controls upon carbonate ramps successions can provide more accurate information to improve depositional models within these systems and their ancient analogs.

**References**


Figure 1. Geographic location and general geomorphology of Isla de Holbox study area. A) Gulf of Mexico regional map with location of Isla de Holbox on the northeast coast of the Yucatan peninsula, Mexico. B) Remote sensing image with location of the study area highlighted in the yellow box. C) Geomorphic elements within study area, location of surficial sediment samples and ADCP meter locations.
Controls on Sedimentation and Diagenesis in Modern Pre-Salt Analogues.

Randy Stotler, Jennifer Roberts, David Fowle, Chris Omelon

SUBSURFACE APPLICATION: Analogs for pre-salt Brazil and offshore Angola
STATUS: Long term project in progress
TIMING: Significant results to be reported to membership January 2017
FUNDING: Full (3 years)

Purpose
Saline groundwater-fed interface environments in arid and semi-arid regions are critical zones of lacustrine and palustrine carbonate precipitation. These areas include chotts, sabkha, salars, salt pans, and alkaline or salt lakes. Although climatic conditions clearly play a first order role in the chemical evolution of these environments, the early diagenetic processes are highly variable and have strong linkages to microbial processes. Reclassification of some lacustrine oil “shales” as carbonates from alkaline lakes, accentuates the importance of gaining insights from modern analogues on the development of these facies (Alonso-Zarza and Wright 2010, Wright 2012). This recent attention has highlighted the variation of microbial build-ups, and the large differences between marine and lacustrine carbonates precluding a “simple comparison” between the two depositional environments (Wright 2012). Mg-silicates, a common precipitate in alkaline lakes, could affect carbonate formation and subsequent preservation, possibly limiting microbial carbonate production (Wright and Barnett, 2014). As a result, it is critical for research to be conducted on facies models related to silicate-carbonate interactions and microbial build-ups (Wright 2012). The goal of this study is to use a group of groundwater fed lakes of varying salinity to study the physiochemical controls on abiotic and microbially mediated carbonate and silicate formation. Studying these processes will lend insight into the formation of microbialites in saline environments, their morphogenesis and potential tool in biostratigraphic correlation, diagenesis and reservoir development, with relevance towards a number of carbonate reservoirs.

Project Description
To develop a depositional model for the pre-salt deposits, it is critical to understand the microbial and geochemical reactions that lead to mineral precipitation and preservation. We are investigating carbonate and Mg-silicate formation and preservation in lakes and sediments through a combination of biogeochemical mineralogical and isotopic analysis and experimentation. Briefly, the carbonate and silicate formation environment in several lakes with varying salinity are characterized by measuring lake chemistry (transects) and pore waters (push cores up to 2 m) for major and trace elements including nutrients, organic carbon and stable isotopes (O, C) (e.g. Crowe et al. 2008). The corresponding filtrate and sediment (or mat) samples are digested for the same parameters and additionally characterize the mineralogy, morphology, and relationships therein (e.g. Phillips-Lander et al., 2013) using XRD, thin sections, TEM, and SEM. Finally lake water is seeded with reactors similar those we have used previously (Lander et al., 2013) with and without microspheres with carboxylated functionalities to investigate microbial carbonate formation in a more controlled fashion in these environments. Associated
research is exploring the evolution of $\delta^{81}{\text{Br}}$ and $\delta^{37}{\text{Cl}}$ in these lakes during early diagenesis.

The differential influences of physiochemical and microbial processes on carbonate formation are currently investigated in a region containing hundreds of compositionally diverse lakes, with dissolved solids ranging from 0.2 g/L to 384 g/L. This environment is ideal because: (1) solute delivery by groundwater has been well characterized and is relatively constant; (2) the lakes represent a large geochemical and salinity variation in a small geographical area, enabling sampling and experimentation in a range of evaporative stages; (3) we now have four years of data recording temporal changes; and (4) the microbial ecology of the lakes will be geochemically rather than biogeographically controlled (e.g. all lakes have access to the same species of microbes). Contingent upon future funding, alkaline lakes beyond this region will be explored to verify observations and conclusions made at this site, improve understanding of diagenesis in these settings, and enhance confidence in the site as an analogue for pre-salt deposits.

Figure 1. One of the alkaline lakes in 2013, with a large salt pan and stranded cyanobacteria. Lake bottom, salt pan, and algal mats at this site have been cored for this investigation.

Deliverables
Specific deliverables include: 1) Development of a new conceptual model of the role of salinity gradients in groundwater – large aquatic ecosystem interfaces with a focus on microbial controls and silicate-carbonate interactions; 2.) Preliminary mechanistic, morphological and kinetic data on in situ of carbonate formation with and without reactive surfaces in the same environment; 3.) a comprehensive bibliography of references pertaining to climatic, tectonic, chemical, microbial, and digenetic controls in
alkaline lakes; and 4.) At least one manuscript and development of a larger NSF or industry supported proposal.

References


Patch Reefs of the Bahama Banks: Distribution, Controls, and Reservoir Potential

Paul Enos and Robert N. Ginsburg (U. Miami)

SUBSURFACE APPLICATION: Reefal reservoirs in Southeast Asia, Iran, Iraq, and the Gulf of Suez
STATUS: New student arriving in 2015
TIMING: New results are available
FUNDING: Past and possible future funding from Total S.A., St. Anselm Exploration, and Ocean Research Foundation, Inc

Purpose
Patch reefs are sufficiently numerous in large areas of the Bahama Banks to create biostromes or bioherms, depending on sea-level fluctuations, with reservoir potential. We seek to document the extent and controls of patch-reef distribution.

Project Description
Reefs have long fascinated geologists, especially petroleum geologists. Geologic, ecologic, and biologic studies have focused on platform-margin reefs (cf. James, 1983; Kiesling et al., 2002). Patch reefs, smaller, less glamorous, and thus neglected, have great potential as rock formers, petroleum reservoirs, and biodiversity refugia. Patch reefs abound in the eastern Great Bahama Bank. The Exuma lobe hosts at least 2200 large patch reefs, readily identifiable with existing imagery (Enos, ms.). The western GBB, Andros lobe, lacks patch reefs (Purdy, 1963; Traverse and Ginsburg, 1966).

We speculate that up to 70,000 patch reefs >10 m diameter (the approximate limit of resolution on available imagery) dot the Exuma lobe alone. Further, the control on patch reef distribution, once the favorable ecologic threshold has been crossed, is the availability of hard substrates for nucleation. Alternatively, the relative fluxes of open oceanic water across the banks may be the key factor or co-factor. Bahaman patch reefs appear capable, in time, of producing economically significant biostromes, with static sea level, or bioherms, with rising sea level.

Verifying the abundance hypothesis depends on acquisition of higher resolution imagery; resolution >1 m is commercially available in some areas, for a price. We also need to expand coverage to areas where we have relied mainly on chart notations for presence or absence of patch reefs. Pinning down the ultimate control, while desirable for prediction as well as scientific peace of mind, may prove elusive. Detailed water-quality data, beyond the scope of this study, might help, but available modern studies have focused on shelf-margin reefs, without earth-shaking revelations. We will expand excavation, coring, and bottom observations to document substrate history and availability, but will probably not be able to exclude alternative hypotheses on control. Biostromes of coarse skeletal debris with preservable primary porosity of 65% already exist in accumulations up to 2.15 km long, 1.2 km in diameter, and 4 m thick (Enos, ms.). Anecdotal evidence for rapid expansion and nucleation of patch reefs suggests the ultimate construction of many discontinuous bioherms of kilometric lateral dimensions and up to 8 m thick at constant...
sea level. Projections and modeling are expected to show that rising sea level would drive vertical accretion, resulting in bioherms ≥ those in the Belize lagoon (James and Ginsburg, 1979), with dimensions and acoustic parameters favorable for exploration.

**Deliverables**

This project will produce georectified maps and images with patch-reef density represented by isopleths for the Great Bahama Bank, accompanied by images and data on specific examples. As the preliminary study was an offshoot of research supported by Total S.A., the proprietary details are in negotiation. An abstract has been released (Enos et al., 2011), so we are optimistic that the preliminary report may be released soon.

**References**


Geochemical and Microbiological Characterization of Carbonate Sediments and Associated Fluids, Crooked-Acklins Platform, Bahamas

Jennifer Roberts and Eugene C. Rankey

SUBSURFACE APPLICATION: Applicable to diagenetic reactions in shallow water, carbonate aquifers.
STATUS: Project Proposed
TIMING: Initial sampling occurred June 2011 with microbiological and geochemical analysis complete. Subsequent data mining and additional sampling are proposed.
FUNDING: Seed funding from KICC awarded.

Purpose
The proposed research will characterize geochemistry and microbiology of carbonate sediments and associated fluids on the Crooked-Acklins Platform (CAP), Bahamas (RANKEY AND REEDER, 2010). The purpose of this project is to compare the geochemistry and microbiology of sediments and fluids collected from a variety of environments (tidal flat, reef, platform interior, shoals, upwelling zones, etc.) with the aim of understanding operative biogeochemical processes that may influence carbonate sedimentation. As Bahamian carbonate platforms are modern analogs for many carbonate petroleum reservoirs, this research is relevant to understanding how and where different types of sediments form, and as a means of better understanding their occurrence in subsurface environments.

Project Description
Carbonate sediments are favored in seawaters that are supersaturated with respect to carbonate minerals, waters which may be influenced by physicochemical processes such as mixing of fluids or evaporation (STUMM AND MORGAN, 1996) as well as microbial activity. The presence of microorganisms is ubiquitous in surface and shallow-subsurface sediments and many studies have documented their participation in carbonate mineral precipitation. Microorganisms drive carbonate mineral supersaturation through a number of metabolic processes (e.g., sulfate reduction, denitrification, photosynthesis; KONHAUSER, 2007) and facilitate mineral nucleation through interaction of microbial surfaces (cell walls and exopolymeric substances) with dissolved ions (Ca$^{2+}$ and Mg$^{2+}$; e.g., BRAISSANT et al., 2003).

Water, sediments and microbial mats were sampled 15 sites in the environments around Crooked Island, Bahamas, in June 2011. Geochemical and functional gene analyses were completed in Fall 2012. Preliminary analyses demonstrate that all sampling sites are phosphorus-limited (Table 1) and C:N ratios range from 2-5 compared to 6.6 for normative Redfield ratio, which is indicative of preferential degradation of nitrogenated organic carbon. Microbial metabolism is dominated by carbon degradation and methanogenesis (Figure 2), and ooid environments are distinguished by a predominance of methanogenesis but lack of genes associated with exopolymeric substance production.
Because of the nature of the complex nature of the functional gene analysis data, we propose the following approach in continuing this project:

- Continued mining of the functional gene analysis data to find linkages between specific sedimentary environments and microbial metabolisms.
- Completion of mineralogic and SEM characterization to constrain $\%\mathrm{MgCO}_3$ incorporation in carbonate sediments and to observe microbe–mineral interactions that may be important for interpreting mineral textures.

Additionally, we aim to undertake field campaigns: 1) targeting specific environments (for example, ooid shoals) to better identify and link specific microbial metabolisms to sediment production; and 2) sampling temporal changes to capture the magnitude and variation in nutrient cycling/limitation and its role in sediment production.

**Deliverables**
The proposed project is a collaborative project between Roberts and Rankey and will integrate their expertise to understand biogeochemical and physical processes operative in modern platform carbonates. This pilot project has identified tantalizing differences in nutrient conditions and active microbial metabolisms in a range of sedimentary environments in the CAP. Our preliminary results lay the groundwork for subsequent studies assessing rates of carbonate sediment precipitation as a function of microbial activity and available nutrients.

**References**


**Table 1.** C:N:P (carbon, nitrogen, phosphorus) molar ratios for sampling locations.

<table>
<thead>
<tr>
<th>Sample Location</th>
<th>$^1\mathrm{C}:\mathrm{N}$</th>
<th>$^2\mathrm{C}:\mathrm{P}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tidal Flat (TF)</td>
<td>3.0</td>
<td>21089</td>
</tr>
<tr>
<td>Turtle Sound (TS)</td>
<td>3.0</td>
<td>28760</td>
</tr>
<tr>
<td>Leeward Beach (UW)</td>
<td>2.5</td>
<td>4181</td>
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<tr>
<td>Bight of Acklins (BA1)</td>
<td>1.8</td>
<td>3620</td>
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<tr>
<td>Bight of Acklins (BA2)</td>
<td>3.2</td>
<td>6107</td>
</tr>
<tr>
<td>Bight of Acklins (BA4)</td>
<td>1.7</td>
<td>28245</td>
</tr>
<tr>
<td>Reef Beach (RF)</td>
<td>3.5</td>
<td>1452</td>
</tr>
<tr>
<td>Fore Reef (FR)</td>
<td>1.7</td>
<td>11241</td>
</tr>
</tbody>
</table>

$^1\mathrm{C}:\mathrm{N}$ ratios for nutrient-rich waters are $\sim$60:7. All samples indicate slight nitrogen limitation in these waters.
\(^2\) C:P ratios for nutrient-rich waters are \(~60:1\). All samples indicate phosphorus limitation in these waters.

**Figure 1.** Sampling sites on the Crooked-Acklins platform (left) and dissolved organic carbon concentration (mmol /L) plotted as a function of

**Figure 2.** Metabolic diversity of microbial populations associated with carbonate sediments in the Crooked-Acklins Platform.