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:
Sediment Dynamics and Geomorphology of a Southeast Asia Isolated Platform: Holocene Layang-Layang Atoll, Malaysia, South China Sea

Thomas Neal, Gene Rankey, and Kim Jakobsen

SUBSURFACE APPLICATION: Numerous reservoirs are from ancient isolated carbonate platforms, including the Miocene of Southeast Asia, Tengiz and other platforms of the former Soviet Union, Devonian of western Canadian Basin, and Silurian of the Michigan and Illinois basins. This system can provide insights and analogues to these ancient reservoirs, but especially for similar Cenozoic coral-algal reef reservoirs of Southeast Asia.

STATUS: Part of a long-term project in progress

TIMING: This phase is in progress, with final report expected by mid-2019

FUNDING: Fully funded

Purpose

Isolated carbonate platforms are common in the geologic record range from the Paleozoic, Mesozoic and Cenozoic, and can include productive hydrocarbon reservoirs. Although the general stratigraphy and depositional facies of these ancient platforms are well known, details of the controls, patterns, and variability of sediment accumulations are less well constrained. Recent regional studies of the South China Sea show the significance of oceanographic processes on the distribution and extent of carbonate platform geomorphic elements - shelf-marginal reefs, patch reefs, reef sand aprons and lagoons (Rankey and Garza-Perez 2012; Rankey 2016). To develop more rigorous predictive conceptual models for carbonate platform sedimentation and their hydrodynamic controls, this study characterizes and numerically models a Holocene atoll offshore Sabah, Malaysia. Better understanding of oceanographic and sedimentary processes controlling isolated carbonate platforms can improve conceptual models of variability in analogous reservoirs.

Project Description

The focus of research is on the atoll of Pulau Layang-Layang which lies 280 km off the north coast of Malaysian Borneo. Located in the equatorial region within the Spratly Island area of the South China Sea, the isolated carbonate platform rises up nearly 1000 m from the surrounding deep ocean. The atoll is ~7 by 2 km, with the long axis trending east-west. Major geomorphic elements include the reef, reef sand apron, patch reefs, and lagoon (Figure 1A). The reef lies near sea level, exposed only during spring low tide. The reef sand apron asymmetrically fringes inside the reef widest (up to 1.5 km) at the east and west ends and narrowest (~50 m) on the south, with depths ranging from 1 to 5 m. The central lagoon is ~4 by 1.3 km with depth ranging from 5 to 18 m. Patch reefs of various sizes are located within the lagoon and on the reef sand apron.

This study integrates remote sensing, field, petrographical and granulometrical observations of surficial modern sediments with climate data, oceanographic observations and hydrodynamic modeling. This project focuses on several specific objectives.
First, the area was mapped using high resolution Quickbird satellite imagery revealed the diversity of carbonate producing biota and geomorphic elements found on Palau Layang Layang and provided the setting for the spatial context for the field survey (sampling strategy and oceanographic sensor placement).

Second, during the field survey in July 2017, 190 surficial samples were collected across transects of the atoll (Figure 1B). Detailed field observations of the coral and other carbonate producing biota, bottom types, physical and biological structures, and oceanographic conditions were also recorded. Following the field survey, petrographic and granulometric analyses of the surficial sediments samples characterized the type and quantity of the grain size, sorting, composition, and abundance for the samples (Figure 1C, 1D, and 1E).

Third, an Acoustic Doppler Current Profiler (ADCP) meter, wave gauges (pressure sensors), light and temperature oceanographic sensors were deployed, recovered after five weeks (approximately one lunar month), and their data recovered and processed. Additionally, a high resolution (~ 2.5 m) bathymetric survey was conducted across the atoll. This information provides the basis to model a range of oceanographic processes on the atoll, and explore origins of geomorphic elements (e.g. reef sand apron) and sediment transport pathways using DHI’s M-21 hydrodynamic modeling software. These sedimentology and hydrodynamic modeling results will be integrated within a GIS framework. This analysis will explicitly compare spatial variability in carbonate production, sedimentology, geomorphologic elements, and hydrodynamics to explore potential linkages.

Finally, no other isolated carbonate platform in the geologic record exactly like modern Pulau Layang-Layang. Thus, using the insights from the modern as a starting point, the ultimate objective is to explore potential geological variances by numerically modeling a suite of conceptual models with different key input parameters and geomorphologies (e.g. wind direction, waves, monsoon patterns, regional currents, sea level changes 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 isolated carbonate platform settings.

**Deliverables**

This study supports the broader multi-year project detailing the influence of oceanographic processes on the sedimentology, geomorphology, biota and sediment transport of isolated carbonate platforms. Specifically, this study details the distribution of biota, sedimentology, climate, and bathymetry of the Holocene isolated carbonate platform in the South China Sea, 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 Layang-Layang system, provides insights into the controls on sedimentologic variability for carbonate platform systems in the rock record. This study supports the
collective efforts of the larger project generating data and insights for conceptual models for heterogeneity in carbonate platform analogs and examining broader changes and oceanographic controls on variability, with the goal to provide more accurate information to improve conceptual depositional models and heterogeneity in their ancient analogs.

References
Figure 1. Remote sensing and petrographic images of Pulau Layang-Layang. A) Interpreted image showing reef, sand apron, and lagoon geomorphic elements. B) Image showing mean grain size of granular sediment (denoted by colored circles at surficial sample locations). Representative petrographic images from each major geomorphic element C) reef, D) reef sand apron, and E) lagoon.
Integrated Field and Modeling Analysis of Oceanographic Controls on Sedimentology of Holocene Ramp Carbonates: Yucatán 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 Southeast Asia analogs.

STATUS: Part of a long-term project in progress

TIMING: Project will be completed with final report by end of 2018

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 Yucatán 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,B) lies on the northeastern coast of the Yucatán 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 Yucatán ramp to the north, and the Laguna de Yalahau, a large (300 km²) protected muddy lagoon to the south (Figure 1C).

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 was 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 (Figures 2 A – F). 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. Sedimentology and hydrodynamic modeling results were then integrated 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 Yucatán. 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 Yucatán, 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 Yucatán 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. Remote-sensing images of the Yucatán Peninsula, Yucatán Shelf, and nearshore geomorphology. A) Location of study area offshore of the northeastern Yucatán peninsula note shallow turbid nearshore water of broad shallow Yucatán Shelf. B) Remote sensing image with location of the Isla de Holbox focus area and highlighted in the yellow box. C) Focus area showing geomorphic elements including upper shoreface, subaqueous dunes, foreshore barrier island with beach ridges, and the lagoon with mangrove fringe. Red circles indicate deployment locations of in situ current meters.
Figure 2. Sedimentologic trends and petrographic images. A) Grain size distribution and B) mud percentage along surficial sample transects. Representative petrographic images from each major geomorphic element C) upper shoreface, D) subaqueous dunes, E) foreshore/shoreface, and F) lagoon.
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 proposed
TIMING: Phase 1 results reported in 2017
FUNDING: Seeking 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 Asian isolated platforms and rimmed shelves, and relate these patterns to controlling processes. The 2016 KICC meeting (published as Rankey, 2016) presented final results from 27 isolated platforms of the South China Sea, and this effort proposes a project that aims to expand 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 m² 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 m² 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 sensing data (<2.5 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, and are available presently on the KICC sponsors web page. Pending additional support, the project plan is to expand to other southeast Asia analogs, including other isolated platforms and rimmed shelves, of the Celebes, Sulu, and Java seas.

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).
Developing Modern Analog Models for Shallow-water Tropical Carbonate Systems in the Rock Record that Developed Under Adverse Photic Zone Conditions, Puerto Rico

Evan K. Franseen, Wilson R. Ramírez Martínez, Students

SUBSURFACE APPLICATION: The various modern heterozoan and photozoan carbonate systems developed around Puerto Rico are analogs for Cenozoic tropical carbonate reservoir systems in the Caribbean (such as the Perla giant gas field, offshore Venezuela) and Indo-Pacific. Lessons from the modern of Puerto Rico can be applied to similar reservoir systems throughout the rock record.

STATUS: Proposed project

TIMING: Long-term research project; initial project 2 years

FUNDING: Seeking funding

Purpose

Current carbonate models applied to the rock record are heavily influenced by studies of modern tropical systems, such as the Bahamas, which consist mostly of photozoan reef systems that develop in clear, warm water photic zone conditions. These models have biased interpretations of tropical carbonate systems in the rock record.

Heterozoan carbonate systems are increasingly being recognized as important petroleum reservoirs in the rock record. Although research on heterozoan systems has accelerated over the last two decades, we still lack understanding of controls on facies types and distribution, stratigraphic architecture, and reservoir character. The understanding of heterozoan systems in low-latitude tropical regions is especially lacking. They are increasingly being recognized in areas that are affected by excess nutrients, and turbid water. In addition, some of these systems can contain abundant photozoan that are able to tolerate higher nutrients, more turbidity and reduced temperatures (herein termed limited photozoan association). To better understand these types of atypical shallow-water tropical carbonate systems developed in the ancient, it is important to study modern analogs to develop models. Puerto Rico is chosen for study because it shows variable development of photozoan and heterozoan biota in shallow-water photic zone environments around the island as a result of natural and human-induced variations in nutrients, turbidity, water chemistry, energy and water temperature.

Project Description

Puerto Rico is ideal for study and development of models because abundant data on sediment and biotic components in shallow-water areas have been already collected around the island (e.g. Figures 1, 2), and expertise and resources are available at the University of Puerto-Rico for further analyses of the data, and for further, targeted study and data collection (e.g. Scanlon et al., 1998; Morelock, et al., 1994; Kågesten, et al., 2015).
An initial phase of study is targeted at assimilating and mapping the data already collected on the different types of heterozoan and photozoan biotic and non-biotic components and sediment in the shallow-water photic zone environments (0 to ~30-50 m depth), and to also relate those distributions to areas of land runoff (both natural and man-made), and oceanographic conditions for which data are available (e.g. water temperature, energy, currents, water chemistry). That data will be used to identify areas for more targeted studies to further document, sample, and map out distributions of heterozoan and photozoan biotic and non-biotic constituents and sediments and to determine the controls on development. To this extent, samples will also be collected to determine organic content, turbidity, water chemistry, and data on geomorphology, water depth, energy, currents, and water temperature will be integrated.

Overall goals of the study are to provide better understanding of the conditions affecting the coastal areas around Puerto Rico, and specifically map out and link differing carbonate system development (photozoan, heterozoan, or combination of both) around the island with the major factors responsible for the variability to develop predictive models that can be applied to the rock record. Some of the Cenozoic carbonate rock systems preserved in Puerto Rico, and regionally around the Caribbean, are tropical shallow-water systems that developed under adverse photic zone conditions (high nutrients, turbid waters), which prevented the development of typical photozoan-dominated reefal systems and instead were dominated by heterozoans and photozoans tolerant of adverse photic zone conditions (limited photozoan association). A better understanding of the modern system in Puerto Rico and the controls on distribution of carbonate facies could better aid in understanding the similar Cenozoic carbonate systems, some of which form important petroleum reservoirs in the Caribbean (e.g. Perla, offshore Venuzuela) and the Indo-Pacific.

**Deliverables**

Specific deliverables for the project include maps, cross sections, and data bases on sediment and biotic component distribution, water depths, geomorphology, spatial relationship to areas of land runoff, organic content, and water conditions (energy, chemistry, temperature, turbidity). Overall, the results of this study will provide data on the controls on deposition and distribution of heterozoan and photozoan facies and predictive models that can be applied to systems in the rock record, including those that form petroleum reservoirs.

**References**


Figure 1. Map of Puerto Rico showing distribution of differing sediment types around the island and locations of river mouths. From Scanlon et al. (2004).

Figure 2. Map showing benthic habitat, biologic cover, and percent cover on northeastern portion of Puerto Rico to the Island of Culebra. From Kagesten et al. (2015).
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 ichnocones (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.
Controls on Sedimentation and Diagenesis in Modern Pre-Salt Analogues

Randy Stotler and Jennifer Roberts

SUBSURFACE APPLICATION: Analogs for pre-salt Brazil and offshore Angola
STATUS: Proposed Project
TIMING: Upon Funding
FUNDING: None

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). Our recent research also suggest the source of CO₂ and the cause of the buildup of CO₂ within lake sediments needs further study. The goal of this study is to investigate the physiochemical controls, including the role of geogenic and atmospheric CO₂ on abiotic and microbially mediated carbonate and silicate formation through a series of laboratory experiments. Studying these processes will lend insight into the formation of microbialites in saline environments, their morphogenesis and potential tool in biostratigraphic correlation, and diagenesis and reservoir development (including methods for identifying locations of CO₂ buildup), 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 sediments through a combination of biogeochemical mineralogical and isotopic analysis and experimentation. Briefly, the carbonate and silicate formation environment is explored in column and evaporation experiments, where salinity, water chemistry, initial sediment mineralogy, atmospheric and fluid temperature, surface water algal and microbiological flora, and CO₂ sources and concentrations are varied. Major and trace elements including nutrients, organic carbon and stable isotopes (O, C, Cl, Br) will be monitored throughout the experiments. 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, and SEM.

**Deliverables**
Specific deliverables include: 1.) Improved understanding of the controls on carbonate and silicate deposition and preservation in alkaline hypersaline lakes; 2.) Mechanistic, morphological and kinetic data on \textit{in situ} of carbonate formation with and without reactive surfaces in hypersaline lakes; and 3.) At least one manuscript and development of a larger NSF or industry supported proposal.

**References**

