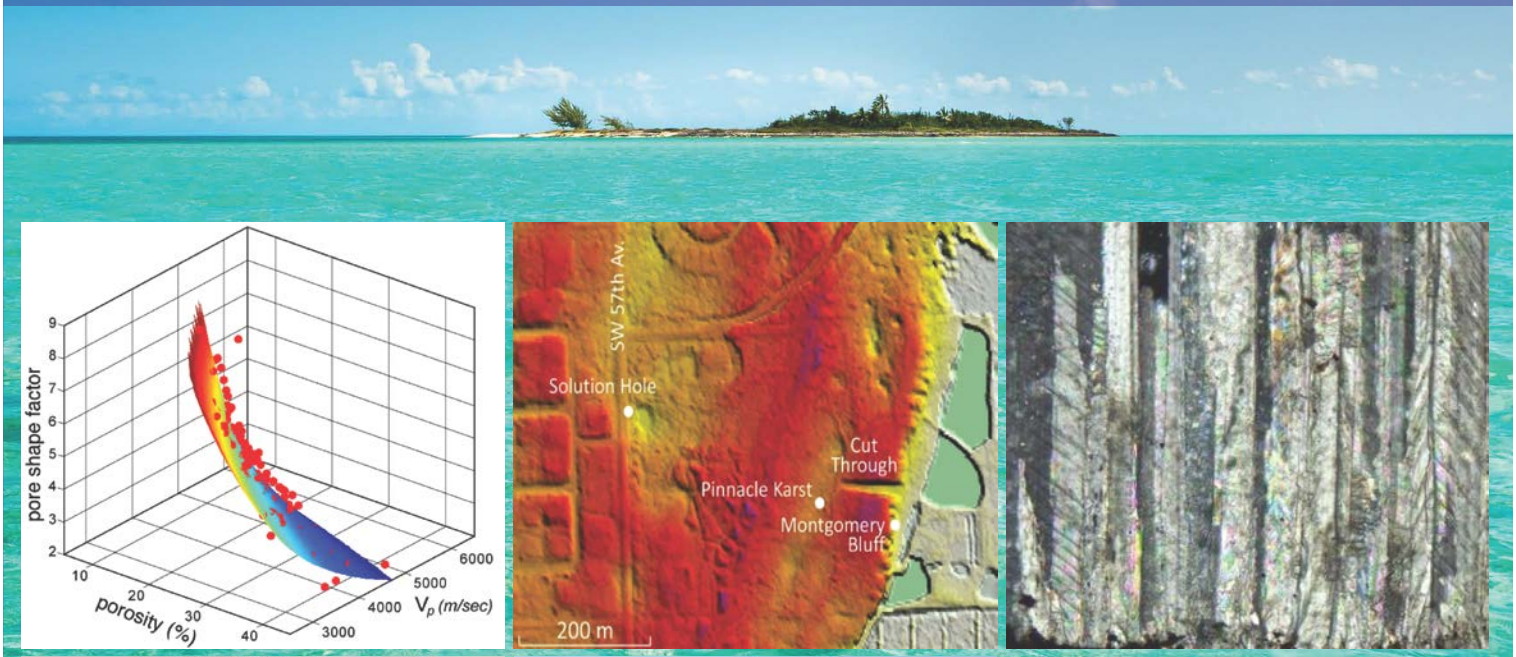
CSL
Center for Carbonate Research
and Education



Prospectus, **2017**

UNIVERSITY OF MIAMI
ROSENSTIEL SCHOOL of MARINE & ATMOSPHERIC SCIENCE

CSL
CENTER FOR CARBONATE RESEARCH

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MISSION OF THE CSL – CENTER FOR CARBONATE RESEARCH

The mission of the CSL – Center for Carbonate Research (CSL-CCR) is to conduct fundamental research for improved carbonate reservoir prediction and characterization.

The research conducted within the CSL-CCR is intended to advance fundamental knowledge in carbonates providing valuable and relevant information for emerging topics in exploration and production. In addition, the CSL-CCR aims to inform its industrial associates on the newest research techniques and topics that potentially can be incorporated into the workflow of projects or help to solve longstanding problems.

The 2017 projects integrate geology, geophysics, geomicrobiology, and geochemistry and combine observational, laboratory, and theoretical research. These integrated studies cover five areas:

- Carbonate Systems and Reservoir Characterization
- Unconventional Reservoirs
- Geochemistry and Diagenesis of Carbonates
- Petrophysics and Near-Surface Geophysics
- Geobiology and Microbialites

The individual projects are designed to address various aspects of these themes. They are described in detail in this prospectus and are retrievable on the website www.cslmiami.info.

KNOWLEDGE TRANSFER

The CSL – Center for Carbonate Research transfers the research results to our industry partners through an annual meeting, our website, and publications.

To increase the knowledge transfer we will start to give webinars with specific topics for geoscientists in the participating companies.

We continue to offer field seminars and short courses.

A Certificate Program in "Applied Carbonate Geology" offers geoscientists to become experts in carbonates.

We present the research results described in the prospectus at the **Annual Review Meeting** and provide each company with a digital version of our presentations and publications stemming from CSL sponsored research. On our **website** research results from previous years can be viewed in the archive section, providing a comprehensive database for many topics and geographic areas. Upon request, we also share original data sets with participating companies.

PERSONNEL

PRINCIPAL INVESTIGATORS

Gregor P. Eberli, Ph.D. 1985, Geological Institute ETH Zürich, Switzerland
Research Interests: Shallow and deep-water carbonate systems, seismic facies analysis and sequence stratigraphy, petrophysics of carbonates, and mixed carbonate/siliciclastic systems.

Mark P. Grasmueck, Ph.D. 1995, Geophysical Institute ETH Zürich, Switzerland
Research Interests: Applied geophysics, reflection seismic, Ground Penetrating Radar, 3-D and 4-D near surface imaging, reservoir characterization.

James S. Klaus, Ph.D. 2005, University of Illinois
Research Interests: Evolution and extinction of Cenozoic to Recent reef corals, paleoecology of Cenozoic reefs, geo-microbiology of modern coral reef ecosystems.

Donald F. McNeill, Ph.D. 1989, University of Miami/RSMAS
Research Interests: Sedimentology and stratigraphic correlation of carbonate and mixed systems, integrated stratigraphy (bio-, Sr-isotope-, magneto-stratigraphy).

Sam J. Purkis, Ph.D. 2004, Vrije Universiteit Amsterdam, The Netherlands
Research Interests: Carbonate sedimentology, remote sensing, GIS, geomodelling, marine biology, marine spatial planning.

Peter K. Swart, Ph.D. 1980, King's College, University of London, England
Research Interests: Sedimentary geochemistry, stable isotope geochemistry, organic geochemistry, global climate change, coral reef sedimentation.

SCIENTISTS

Mara R. Díaz
Paul (Mitch) Harris
Greta Mackenzie
Ralf J. Weger

SCIENTIFIC COLLABORATORS

G. Michael Grammer	Oklahoma State University
Christian Betzler, Thomas Lüdmann	University of Hamburg, Germany
Dierk Hebbeln and colleagues	University of Bremen, Germany
Thierry Mulder and colleagues	University of Bordeaux, France
John Higgins	Princeton University

STUDENTS

Sean Ahearn, Emad Alothman, Sara Bashah, Brandon Burke, Viviana D. Díaz, Kimberly C. Galvez, Emma Giddens, Sharmila Giri, Anna H.M. Ling, Sevag S. Mehterian, Chelsea L. Pederson, Laura Rueda, Jara S.D. Schnyder, Philip T. Staudigel, Max Tenaglia, Mustafa K. Yuksek

POST DOCTORAL ASSOCIATE

Sean Murray

RESEARCH ASSOCIATE

Amel Saied

STAFF

Karen Neher	Office Manager
Chris Kaiser	Technical Specialist

CERTIFICATE PROGRAM: *APPLIED CARBONATE GEOLOGY*

Department of Marine Geosciences, Rosenstiel School of Marine and Atmospheric Science

PURPOSE AND GOALS OF THE CERTIFICATE PROGRAM

The goal of the Certificate Program is to provide first-rate continuing education to professionals or geology students who want to become experts in carbonate geology. To reach this goal courses are offered in carbonate sedimentology, seismic stratigraphy, petrophysics, and geochemistry for an advanced knowledge and understanding in carbonate systems.

OVERVIEW AND COSTS

A Certificate in *Applied Carbonate Geology* requires the successful completion of 16 course credits assembled from 10 courses in the program (see below). The courses combine classroom teaching, laboratory classes and applied projects. No thesis will be written.

Courses for the Certificate Program will be offered in the Spring Semester and the 1st Summer Session of 2017. The student/geoscientist will be in residence for 6 months. The current tuition fee is $1900/credit.

REQUIREMENTS FOR ADMISSION AND REGISTRATION

A bachelor degree or equivalent degree is required but can be offset by years of working experience. No GRE or TOEFL are required.

Registration for the Certificate Program will start in the summer of 2016 and will be handled by the Graduate Studies Office of RSMAS.

INSTRUCTORS IN THE CERTIFICATE PROGRAM

The instructors of the courses in the Certificate Program are the faculty and scientists of the CSL - Center for Carbonate Research.

OFFERED COURSES IN THE CERTIFICATE PROGRAM

MGS 611	3 Cr	Earth Surface Systems
MGS 641	2 Cr	Field Evaluation of Fossil Platforms, Margins, and Basins
MGS 678	2 Cr	Field Seminar: Facies Successions on Great Bahama Bank
MGS 688	2 Cr	Field Seminar: Heterogeneity of a Windward Margin
MGS 784	2 Cr	Seismic Interpretation of Carbonate Systems
MGS 785	2 Cr	Petrophysics of Carbonates
MGS 786	2 Cr	Microbial Carbonates
MGS 787	2 Cr	Carbonate Diagenesis and Petrography
MGS 788	2 Cr	Analysis of Carbonate Cores and Logs
MGS 601	1 Cr	Seminar in MGS

The syllabus of each course is posted on the CSL and RSMAS websites. The two field seminar courses are identical to the annual Bahamas field seminars that were offered every year.

2017 RESEARCH FOCUS

Sam J. Purkis has joined the CSL – Center for Carbonate Research and thus his research interests which focus on modern shallow-water carbonate systems are now an integral part of our research effort in carbonate systems. Together with Paul M. (Mitch) Harris he is working on two projects that use quantitative interrogation of depositional patterns from remote sensing data to elucidate spatial heterogeneity in ooid shoals and hydrodynamic modeling of the bank top deposition. Dimensions and processes of modern slope and basin environments are the focus of three projects. They rely on morphometric analysis of multibeam bathymetry and single-channel seismic data that is calibrated by images from remotely operated vehicles and gravity cores. A common thread in all three studies is the assessment of currents on the sediment distribution. The role of currents is also investigated in a new project in the platforms of the Luconia province and in the Maldives.

With regards to reservoir characterization, the focus is on the petrophysical characterization of strata from the shallow to the deep and from different ages. In some areas we complement existing data with new data but the major effort is to exploit the vast CSL data base to assemble a comprehensive catalogue of the mechanical and petrophysical properties and their interconnected relationships. We trust that this database is useful for various types of modeling.

Other petrophysical and near-surface geophysical studies are part of larger research initiatives, although they target some fundamental rock physics problems. In the unconventional research initiative in the Neuquén Basin we investigate the acoustic anisotropy and electrical resistivity of unconventional reservoir facies. In the Maldives research initiative we test the Extended Biot Theory that potentially relates acoustic properties to permeability.

The formidable data set from the Miocene platform and drift deposits in the Maldives that was collected during IODP Expedition 359 is the basis for several projects. The strong currents sweeping across the atolls of the archipelago in the Maldives control the deposition in the Inner Sea. The CSL projects will concentrate on these drift deposits examining their origin, characterizing the lithology and their petrophysical properties, including a new mechanism of porosity formation in aragonite-rich sediments. Another study is testing the hypothesis that the onset of strong ocean currents causes the demise of carbonate platforms.

We continue using the Vaca Muerta strata in the Neuquén Basin in Argentina to address several fundamental questions in unconventional plays. We expand the array of sections measured in the basin center near Puerta Curaco to assemble a high-quality complete section and assess the variability of the strata in this location. Additional short cores from these sections will aid in this effort and will be used for high-resolution geochemical and petrophysical characterization of the unconventional rocks. The goal is to achieve a robust outcrop-subsurface correlation for the Vaca Muerta Formation.

In addition to providing analytical services for many of the projects outlined in this prospectus, the geochemistry group is concentrating in three areas, (i) clumped isotopic analyses, (ii) the application of C, S, and B isotopes to the sedimentary record, and (iii) the control on the distribution coefficient in biogenic and non-biogenic systems. In the clumping projects we are continuing to investigate the use of the clumped isotope temperature proxy in order to understand, in particular, the diagenesis of dolomitization and early meteoric processes. We also want to add a

new generation clumping instrument and automate the process. Our long interest in the use of C isotopes as a stratigraphic tool has stimulated interest in the isotopes of B and S and all three proxies are being studied during well-constrained diagenetic scenarios. Finally, we are growing corals within seawaters of differing Mg/Ca and S/Ca ratios. The aim is to study influences on trace element distribution and such results may serve as an analogue for inorganic systems.

Below is the list of all planned projects. The detailed objectives and deliverables of each project are outlined further in the 2017 research prospectus.

2017 PLANNED PROJECTS

CARBONATE SYSTEMS AND RESERVOIR CHARACTERIZATION

- Hydrodynamic Model for Isolated Carbonate Platforms
- Quantitative Interrogation of Depositional Patterns and Diagenetic Modification of the Miami Oolite
- Geomorphometry along Western Great Bahama Bank - Plunge Pools and Cyclic Steps
- Composition and Growth Patterns of Cold-water Coral Mounds in the Straits of Florida
- Habitat Map and Geomorphometry of East Campeche Bank: A Proxy for Current Directions
- South China Sea Oceanographic Impact on the Luconia Platforms Offshore Sarawak, Malaysia
- Deciphering the Evolution of the New Providence Platform, Bahamas, Using 2D GPR Data and Core Correlation
- Calcite Concretions to Refine the Marine-to-Nonmarine (Sequence) Boundary
- Deconstructing the Sedimentology of Mixed Carbonate-Siliciclastic Deposition: Cibao Basin, Dominican Republic
- Petrophysical Properties of a Fringing Reef Margin
- Assemble Comprehensive Database of Mechanical and Petrophysical Properties of Platform Carbonates

PROJECTS FROM IODP EXPEDITION 359

- Projects from IODP Expedition 359 - Maldives Platform and Current Deposits (Year 2)
- Petrophysical Calibration of the Coarse-Grained Carbonate Drift Fan, Maldives
- Influence of Ocean Currents on Miocene Carbonate Platform Drowning
- The Formation of Celestine: A Possible Mechanism for the Creation of Porosity in Platform Derived Sediments
- Testing the Extended Biot Theory in Carbonates of the Maldives
- The Origin of Organic Rich Layers in the Maldives

UNCONVENTIONAL RESERVOIRS

- The Vaca Muerta Research Initiative (Year 3): Neuquén Basin, Argentina
- Lateral Facies Variability and Thickness Changes in a Basinal Setting

- Depositional and Environmental Controls on Organic Material in the Vaca Muerta Formation
- High Resolution Elemental, Mineral and Isotopic Assessment of Cycles of the Vaca Muerta Formation, Argentina
- Temperature of Formation of the Vaca Muerta "Beef" Determined by Clumped Isotopes
- Acoustic and Electrical Property Characterization of the Vaca Muerta Formation

GEOBIOLOGY AND GEOCHEMISTRY

- Geomicrobiology of Holocene Freshwater Microbial Mud in the Florida Everglades
- Using Clumped Isotopes to Constrain Diagenetic Temperatures in Oceanic and Periplatform Carbonates
- Effects of Seawater Mg^{2+} and Ca^{2+} Concentrations on Sr, Mg, and S Elemental Partitioning in Scleractinian Corals
- Boron and Sulfur Isotopes: Original Signals or Diagenetic Indicators?
- Clumped Isotopes: The Future

COSTS

The contribution of each Industrial Associate towards the research is **$55,000**. The CSL-CCR raises additional research grants from national funding agencies such as the National Science Foundation and the Petroleum Research Fund for many of the proposed projects. For example, funding for the data acquisition of the deep-water carbonates project, and most of the funds for new equipment for the geochemical studies, have been made possible by grants from federal funding agencies.

2017 REPORTING

WEBINARS

Although we had not many takers in 2016, we continue to offer webinars to our industrial associates to facilitate knowledge transfer at low cost. Each webinar will cover one topic and will consist of a presentation and a question and answer portion. Interested companies can request the webinar and the topic. For example, in 2016 Peter Swart presented a webinar on the application of clumped isotopes, and Gregor Eberli gave a webinar about the importance of pore-structure for petrophysical properties in carbonates and microbialites.

ANNUAL REVIEW MEETING AND FIELDTRIP, OCTOBER 2 - 5, 2017

The results of the projects detailed in this prospectus will be presented at the **Annual Review Meeting in Miami, October 2 - 3, 2017**. In conjunction with the meeting we will have a fieldtrip on **October 4 - 5, 2017.** We will send out information on the logistics for the meeting and the tentative program in the second quarter of 2017.

REVIEW MEETING FIELDTRIP, FLORIDA KEYS AND FLORIDA BAY, OCTOBER 4 – 5, 2017

In conjunction with the annual review meeting, this year's fieldtrip will be to the **Florida Keys** and **Florida Bay**.

The theme of the **Florida Keys** portion of the field trip is the Pleistocene reef development and the sedimentary record of the oscillation of sea level during the last interglacial (MIS5e) (Fig. 1). During the fieldtrip we will present the results from an ongoing collaborative project with Andrea Dutton of the University of Florida where we drilled cores on in the Keys. We will visit the adjacent outcrops and discuss the implications for cycle stacking and diagenesis of the short-term exposure during the oscillation.

The day in **Florida Bay** (Fig. 1A) will illustrate the sedimentary record of the Holocene transgression. Abundant lime mud is deposited in the low-energy, shallow shelf, forming mud islands and basins that document the uneven filling

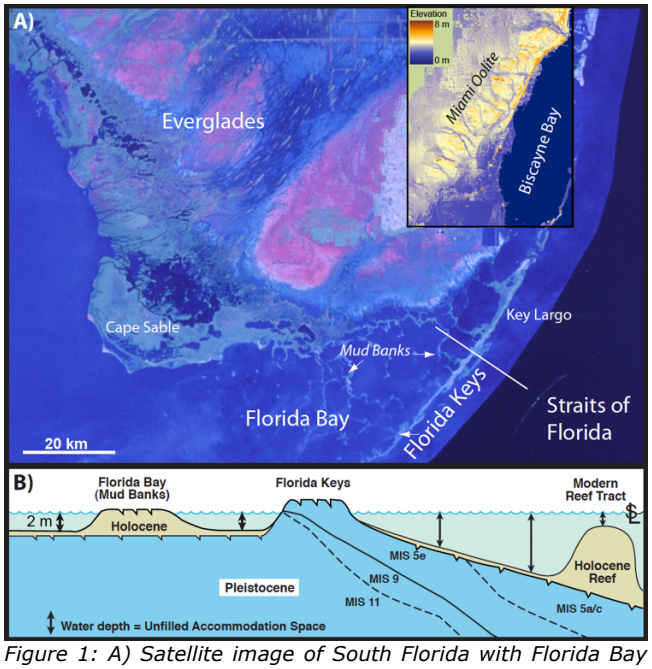

Figure 1: A) Satellite image of South Florida with Florida Bay and the bordering Florida Keys and Everglades. B) Schematic cross-section from the Florida Reef Tract into the bay, illustrating the stratigraphic relationship between the Holocene and Pleistocene.

of the accommodation space and the creation of depositional topography in this low energy environment. We will discuss the implications of unfilled accommodation for cyclo-stratigraphy and depositional modeling. Florida Bay is also interesting with regards to the hydrographic conditions that change seasonally and influence the formation of mud and the subsequent diagenesis. The mud islands harbor a diverse microbial community and are often capped by microbial mats. We will present the influence of both the waters and microbial community on the early diagenesis in these mud accumulations.

HYDRODYNAMIC MODEL FOR ISOLATED CARBONATE PLATFORMS

Sam J. Purkis, Georgenes Cavalcante[1], Liisa Rohtla[2], and Paul (Mitch) Harris

1) Instituto de Ciências Atmosféricas, Universidade Federal de Alagoas, Maceió/AL, Brasil,
2) Nova Southeastern University Oceanographic Center, Fl., U.S.A

PROJECT OBJECTIVES

- Combine the MIKE hydrodynamic model with facies maps for the Cay Sal Bank (CSB) and Great Bahama Bank (GBB) to examine the development of hiatal surfaces.
- Derive accurate bathymetry for Little Bahama Bank (LBB) so that it may be included in the model domain.
- Expand the analysis of MODIS imagery to audit whitings on the CSB and LBB to explore synchronicity with events on the GBB.
- Run the MIKE model for the Pleistocene S. Florida shelf to explore hydrodynamic control on the Miami oolite.

PROJECT RATIONALE

Purkis et al. (2016) initiated a two-year project utilizing MIKE 3, a hydrodynamic model, to simulate flow across the GBB and CSB (Fig. 1). The motivation was threefold. First, to examine the degree to which off-platform ocean climate influences platform-top hydrodynamics. The model suggested that the Florida Current (FC) makes episodic but meaningful excursions atop both the CSB and GBB. Second, to investigate the ability of the model to predict the accumulation of oolitic sand complexes along the margin of the GBB, with the outcome that the areal extent of sand bodies is well differentiated by the MIKE current velocities. Third, the ability of the MIKE model was trialed to forecast the initiation/suppression of whitings events atop the GBB (drifting patches of lime mud). This question is pertinent considering that the trigger for whitings events remains controversial, but they are calculated to have immense significance for the production and accumulation of muds on the Bahama banks. By analogy, whitings were likely significant for the lime mud budget of ancient platforms also. Comparative analysis using the MIKE model and whitings tallied from MODIS satellite imagery suggest that strong incursions of the FC atop the GBB serves to suppress the formation of whitings, but that areas lacking any influence from that current (such as the precinct of the GBB in the lee of CSB) are not conducive to whitings events. These results suggest a complex dependency on whitings formation and renewal of platform-top waters by surrounding ocean circulation.

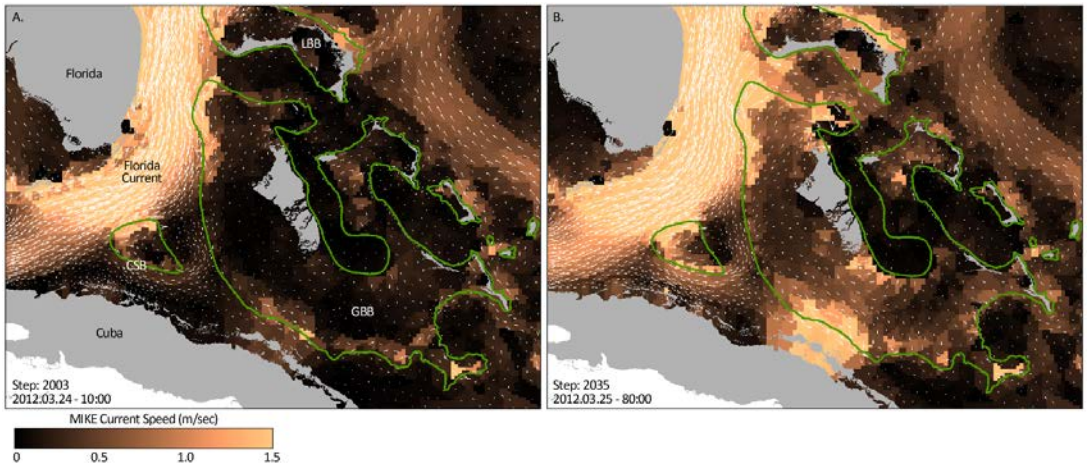

Figure 1. Temporal variation in the influence of the FC atop the CSB and GBB during March, 2012. (A) Shows limited incursion, whereas (B) reports meaningful connection between off-platform circulation and platform-top hydrodynamics.

SCOPE OF WORK

Hydrodynamic Model and Remote Sensing - The domain of the MIKE 3 model will be developed to incorporate the LBB and the examination of whitings from MODIS will be expanded to cover the LBB and CSB. Particular attention will be paid to synchronicity in the seasonal variation of whitings between the GBB, LBB and CSB and possible control by variations in intensity of the FC. The MIKE model will also be trialed atop the MIS 5e Florida Shelf with reference to established sea-level curves in order to examine hydrodynamic control of the deposition of the Miami oolite.

Sediment Transport Model - In order to evaluate sediment movement, the MIKE hydrodynamic model will be merged with depositional facies maps (Harris et al., 2015). The sediment transport model will be used to compare and contrast flow simulations with patterns of sediment fill of accommodation space across the platform tops of the GBB and CSB.

SIGNIFICANCE

An improved understanding of hydrodynamic control over platform-top sedimentation can only refine our general depositional models for platform carbonates, and lead to an enhanced use of these analogs in subsurface characterization and modeling.

REFERENCES

Harris, P.M., Purkis, S.J., Ellis, J., Swart, P.K., and Reijmer, J.J.G., 2015, Mapping water-depth and depositional facies on Great Bahama Bank: Sedimentology, v. 62, p. 566-589.

Purkis, S.J., Cavalcante, G., Rohtla, L., and Harris, P.M., 2016, Hydrodynamic model for isolated carbonate platforms: CSL Annual Review Meeting Abstracts Volume, p. 27-33.

QUANTITATIVE INTERROGATION OF DEPOSITIONAL PATTERNS AND DIAGENETIC MODIFICATION OF THE MIAMI OOLITE

Paul (Mitch) Harris and Sam J. Purkis

PROJECT OBJECTIVES

- Exposure of the Miami oolite in the vicinity of Miami, Florida, provides excellent examples for analysis of preserved primary sedimentary features and subsequent diagenetic changes of a "fossilized" ooid sand body.
- Continued analysis of the depositional patterns and stratigraphy of the Miami oolite from interrogation of outcrops, cores, and ground penetrating radar (GPR) within the framework of an airborne LiDAR digital terrain model (DTM).
- Investigation of the varied styles of karst overprint of the outcrops and the amount of modification to the depositional profile.

PROJECT RATIONALE

Harris et al. (2011) quantitatively analyzed three of the main modern carbonate sand bodies on Great Bahama Bank (GBB), which show a range of depositional facies patterns typifying modern deposits as well as their ancient counterparts. Their work introduced several interrogation approaches that we (Purkis and Harris, 2016) applied to the fossil shoals of the Miami oolite as resolved in a LiDAR bare-earth terrain model as the first part of a 2-year project (Fig. 1). The comparison between the modern examples and the Pleistocene deposits of the Miami oolite also explored the preservation potential of various aspects of grainy carbonate systems.

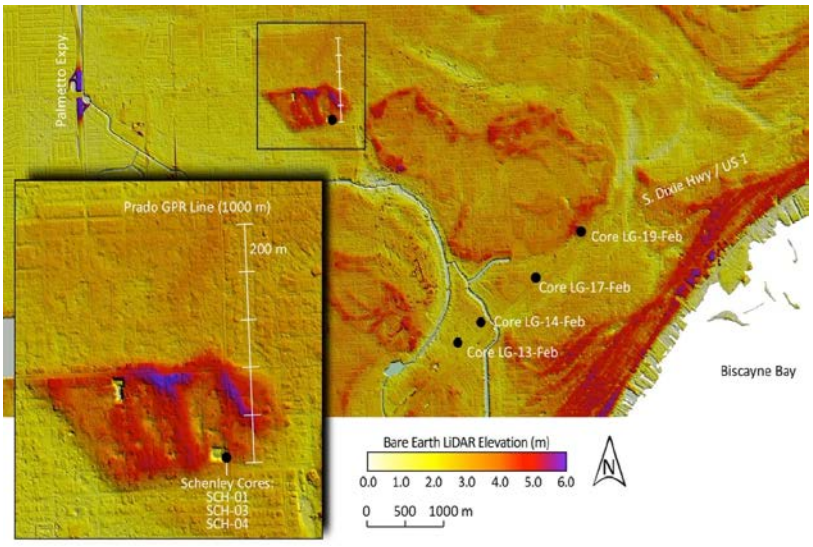

Figure 1. Example of superb resolution of the airborne LiDAR DTM. A NE-SW trending high ridge – the barrier bar of the Maimi oolite – occurs in front of bars and channels (partially shown here) that trend perpendicular to the strike of the sand body. Locations of some cores and a GPR line are shown.

SCOPE OF WORK

Mapping of Miami oolite shoals in the LiDAR DTM uses similar techniques as employed on the imagery from GBB, except that thresholds in elevation values are used to delineate features as opposed to spectral Landsat values. We will continue our analysis of the depositional patterns of the fossil shoals and channels by further investigating key outcrops, which are precisely positioned on the DTM. We will also continue to evaluate the stratigraphy of the Miami oolite, deposited during Pleistocene Marine Isotope Stage 5e, by evaluating key cores and GPR lines within the framework of the DTM, as well as morphometric comparisons to modern analogs in the Bahamas. The DTM and outcrops also offer a unique opportunity to analyze the varied styles of karst overprint and amount of diagenetic modification to the depositional profile during the >100 ky of subaerial exposure (Fig. 2).

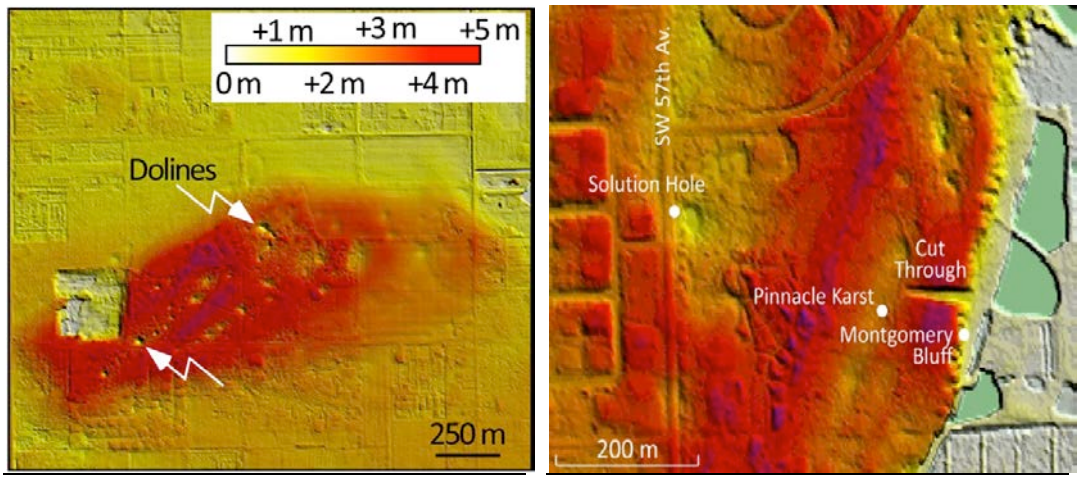

Figure 2. Scenes from the LiDAR DTM showing regions of the Miami oolite where karst features are well developed.

SIGNIFICANCE

Continued interest in modern and outcrop analogs for carbonate sand reservoirs is warranted based on the substantial number of these types of reservoirs. The spatial variability of depositional environments and early diagenetic overprint that potentially creates reservoir heterogeneity within a fossilized carbonate sand system can be interrogated in the Miami oolite.

REFERENCES

Harris, P.M., Purkis, S.J., and Ellis, J., 2011, Analyzing Spatial Patterns in Modern Carbonate Sand Bodies from Great Bahama Bank, Journal of Sedimentary Research, v. 81, p. 185-206.

Purkis, S.J., and Harris, P.M., 2016, Morphometric Comparison of the Miami Oolite and Modern High-Energy Sand Bodies of Great Bahama Bank, CSL Annual Review Meeting Abstracts Volume, p. 133-138.

GEOMORPHOMETRY ALONG WESTERN GREAT BAHAMA BANK – PLUNGE POOLS AND CYCLIC STEPS

Jara S.D. Schnyder, Gregor P. Eberli, Christian Betzler[1], Linda Schiebel[1], Sebastian Lindhorst[1], and Marco Wunsch[1]
[1] *University of Hamburg, Germany*

PROJECT OBJECTIVES

- Analyze morphobathymetric dimensions and distribution of plunge pools as well as steepness and orientation of associated cyclic steps on the lower slope.
- Assess influence of plunge pool and sediment ridge geometry on sediment distribution along the slope.
- Perform integrated morphometric analysis (multibeam bathymetry, backscatter data, sediment samples) as proxies for regional currents and resultant sediment distribution.

PROJECT RATIONALE

Facies heterogeneity along the slopes of carbonate platforms is a result of the interplay between platform-derived gravity-driven sediment transport and the sediment distribution parallel and down-slope by benthic and cascading density currents, respectively (Betzler et al., 2014; Wunsch et al., 2016). The interaction of bottom currents and the seafloor sediments result in characteristic bedforms. The morphology and dimensions of these bedforms depend on current velocity and sediment grain size. Plunge pools, associated sediment ridges, and cyclic steps are sediment features that require high-gradient slopes and a down-slope current system to develop. They might also play an important role in the stratigraphic architecture and facies distribution. High-resolution multibeam bathymetry data, backscatter, and sediment samples along the slope of Great Bahama Bank (GBB) provide an ideal dataset to study topography-current interactions and the sediment distribution and assess the dimensions of the various sedimentary features.

PROJECT DESCRIPTION

High-resolution bathymetry together with sediment samples, collected on several research cruises, provide an opportunity to analyze the heterogeneity of slope facies along GBB. The resolution of the datasets allows the seafloor to be assessed for topographic features and bedforms formed by currents. On the upper slope over 200 plunge pools were identified in the bathymetric data along with hundreds of furrows, funnels, channels, and ridges (Fig. 1). Further downslope sediment wave fields are interpreted as cyclic steps. We plan to assess shape, extent, frequency, and distribution of all these features and their possible role as a sediment sink for material along high-gradient slopes. The aim is to systematically classify and quantify morphologic features indicative of current activity and put them in context with slope inclination and orientation.

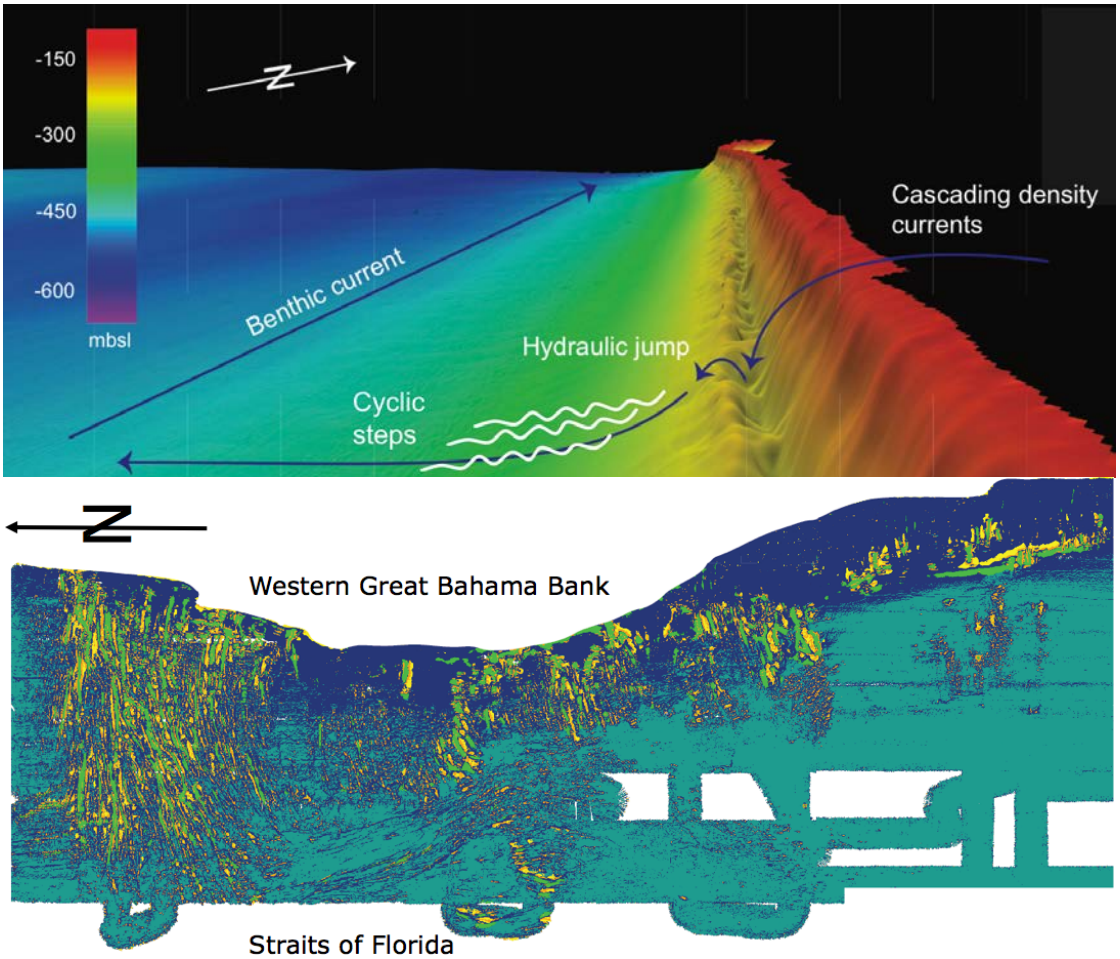

Figure 1. Top: Bathymetry of the steep slope of southwestern Great Bahama Bank with regularly spaced plunge pools and sediment ridges at the base of the escarpment and downslope cyclic steps. Bottom: Example of the use of marine geomorphometry to map and classify topographic features like furrows, ridges, crests, and depressions along the slope and adjacent basin of western Great Bahama Bank.

SIGNIFICANCE

Capturing the dimensions and arrangements of plunge pools and cyclic steps along with other topographic features such as ridges, furrows, and crests will help identify conditions that influence sediment distribution. The aim of this study is to establish a model for slope sediment deposition and distribution along steep-sided carbonate platforms that provides the dimensions of the sedimentary bodies and quantifies the role of cascading density currents and benthic currents.

REFERENCES

Betzler, C., Lindhorst, S., Eberli, G.P., Lüdmann, T., Möbius, J., Ludwig, J., Schutter, I., Wunsch, M., Reijmer, J.J.G., and Hübscher. C., 2014, The periplatform drift: The combined result of contour current and off-bank transport along carbonate platforms, Geology v. 42, p. 871–874, doi: 10.1130/G35900.1.

Wunsch, M., Betzler, C., Lindhorst, S., Lüdmann, T., and Eberli, G.P., 2016, Sedimentary dynamics along carbonate slopes (Bahamas archipelago), Sedimentology, Accepted Article, doi: 10.111/sed.12317.

COMPOSITION AND GROWTH PATTERNS OF COLD-WATER CORAL MOUNDS IN THE STRAITS OF FLORIDA

Kimberly C. Galvez, Gregor P. Eberli, Jürgen Titschack[1],
and Claudia Wienberg[1]
[1)] *MARUM, University of Bremen, Germany*

PROJECT OBJECTIVES

- Determine ages and growth rates in both the Matterhorn and Mount Gay cold-water coral mounds.
- Ascertain if the pattern of pulses of coral growth relates to changes in seawater chemistry using isotopic signatures.
- Assess the variability of species diversity in the two CWC mounds.

PROJECT RATIONALE

Cold-water corals (CWC) and associated facies are important carbonate sediment producers on the sea floor of most ocean basins. This carbonate factory has only been recently recognized and many questions remain with regards to the sedimentation and growth rates of the CWC mounds. This study aims to assess the growth rates of two cores that were retrieved from CWC mounds in the Straits of Florida. We will date both cores and test if the grain size differences in the matrices are related to current strength variations in the Straits of Florida at both sites. In addition, we will assess if coral species change with the glacial cycles and mound site.

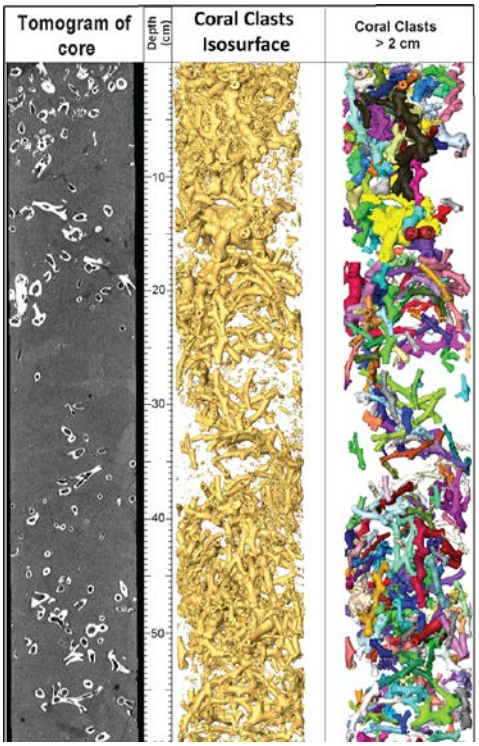

Figure 1. CT scan of 60 cmbsf of Mt. Gay with matrix removed and individual corals distinguishable.

BACKGROUND

One core, 7.03 m in length, was recovered from the flank of the 110 m high "Matterhorn" mound in 770 m water depth. It is composed of an unlithified succession of coral floatstone within a coarse-grained matrix of variable composition. The second core, 3 m in length, was collected from the top of "Mount Gay" mound in 630 m water depth and consists of unlithified coral floatstone within a fine-grained matrix.

The base of the Matterhorn mound core is over 500k years old with coral growth through glacial and interglacial cycles, although intervals of interrupted growth are observed within the core. Mount Gay is significantly

younger than the Matterhorn, reaching only ~10k years at the core base (Wienberg, personal communication). There are little to no interruptions within the Mount Gay core indicating that coral growth was continuous throughout the development of the mound.

APPROACH AND WORK PLAN

To address the questions surrounding growth patterns of cold-water coral mounds in the Straits of Florida we will perform additional age determination on the two cores in hand.

U-Th age-dating and isotopic signatures of the various layers will provide the timing of coral growth in both cores, and interruptions of growth in the Matterhorn core. Existing age dates document growth of these CWC throughout glacial and interglacial periods indicating that climate forcing was not the dominant factor in the CWC growth in the Straits of Florida.

The composition of the two CWC mounds is different despite being located within the same seaway. Grain size analysis of the matrix will be conducted in detail to assess if variations in current strength were coincidental with mound growth. The Mount Gay core displays a dense, fine-grained matrix while the Matterhorn core is coarse-grained. Using the high resolution CT scan of the Mount Gay core, CWC clast content as well as shape, size, and orientation of each coral fragment can be quantified (Fig. 1). The same technique will be used on the Matterhorn core to have an accurate comparison.

Because there might be differences in the coral species diversity, we plan to compare coral species in glacial and interglacial periods in both mounds.

SIGNIFICANCE

The recognition of CWC growth in the Straits of Florida during both glacial and interglacial times is rather unusual as many CWC provinces display a preference for one or other of the glacial intervals; e.g. in the Gulf of Cadiz CWC prefer glacial times, whereas on the Irish margin they prefer interglacial (Dorschel et al., 2005; Wienberg et al., 2010). Yet, the coral growth in the Matterhorn is interrupted by periods of non-growth while Mount Gay displays continuous coral growth pointing to another environmental control for coral growth.

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HABITAT MAP AND GEOMORPHOMETRY OF EAST CAMPECHE BANK: A PROXY FOR CURRENT DIRECTIONS

Jara S.D. Schnyder, Kimberly C. Galvez, Gregor P. Eberli, Dierk Hebbeln[1], Paul Wintersteller[1], and Claudia Wienberg[1]

1) MARUM Bremen, Germany

PROJECT OBJECTIVES

- Geomorphometric analysis and topographic classification of the multibeam data of Campeche Bank.
- Develop a hydrodynamic model in order to obtain a proxy for local/regional currents and relate to coral-habitat distribution.

PROJECT RATIONALE

Campeche Bank, the submerged remnant of a larger bank that drowned in the Mid-Cretaceous, and the adjacent Yucatan Strait are under the influence of two current systems; 1) the northbound Loop current and 2) a benthic countercurrent underneath (Hübscher et al., 2010). High-resolution current models (NOAA) display two dominant current directions affecting Campeche Bank seasonally (Fig. 1). On the upper slope of the Campeche Bank a large cold-water coral (CWC) province exists in intermediate water depths of 500 to 600 m where 20–40 m high elongated coral mounds are arranged in a honeycomb fashion (Hebbeln et al., 2012). The CWC province is located where upwelling, a dynamic bottom current regime, and a physicochemical setting provide ideal conditions for coral growth (Hebbeln et al., 2014). This project tests the hypothesis that sediment distribution and sea-floor-mound topography are directly related to the current system in their orientation.

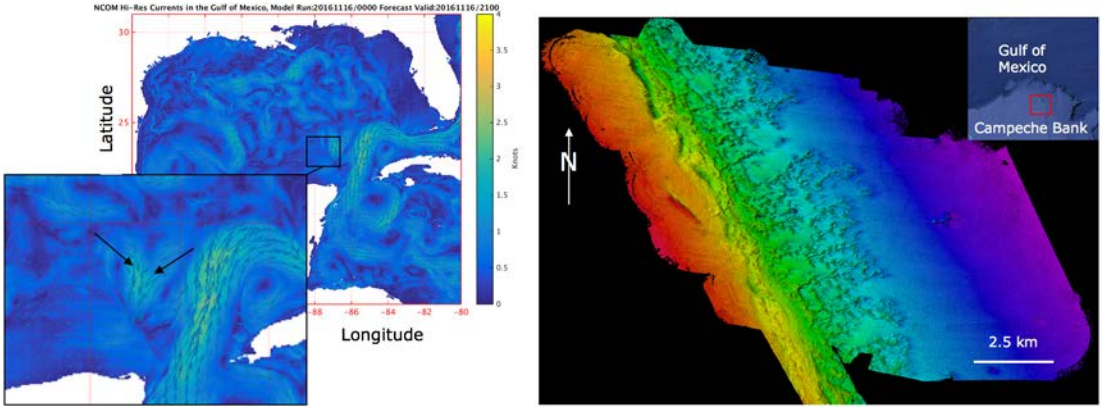

Figure 1. Left: NCOM high-resolution current model in the Gulf of Mexico (from NOAA). Right: Multibeam bathymetry of the upper slope of the Campeche Bank slope with cold-water coral ridges that are onlapped by the muddy sediments of the middle slope. The alignment of the ridges is likely the result of the current directions across this part of the slope.

Cold-water coral ecosystem of Campeche Bank

In the Campeche CWC province coral colonization preferentially occurs from the mid-slope of the elongated mounds towards the peaks (Hebbeln et al., 2012). Coral rubble is deposited on the flanks of the mounds interfingering with a muddy seabed, and small coral thickets grow within the muddy areas where coral rubble is exposed. The pelagic ooze is transported in a NE flow and is collected between the coral-covered ridges and in the lower portions of the slope forming a mud-draped seabed (Hebbeln et al., 2014).

Faunal assemblages consist of *Enallopsammia profunda* and *Lophelia pertusa* as the dominant reef-building framework. *E. profunda* thickets form at the mid-slope region while towards the peak of the mound, *L. pertusa* is more dominant (Hebbeln et al., 2012, 2014). The frameworks are mostly built from individual colonies, however, secondary fusion is observed from a number of coral colonies to form a larger structure. Numerous other benthic organisms are reliant on these CWC reefs including crinoids, anemones, echinoderms, sponges, decapods, fish, and crustaceans.

WORK PLAN

High-resolution multibeam bathymetric data and sub-bottom profiles acquired during MSM 20-4 show that the CWC-ridges are aligned in a bidirectional way, resulting in an apparent honeycomb pattern" (Fig. 1). In this study we plan to perform a classification of the topographic elements and geomorphometric analysis of their orientation as a proxy for current direction. The preferential alignment of CWC due to feeding purposes will help establish the habitat map for the region. The results will be compared to currently used hydrodynamic models.

SIGNIFICANCE

The goal of the study is to relate morphometric features to physical (current) and biological processes that might be a guide for interpreting current regimes from seismic data.

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SOUTH CHINA SEA OCEANOGRAPHIC IMPACT ON THE LUCONIA PLATFORMS OFFSHORE SARAWAK, MALAYSIA

Sara Bashah and Gregor P. Eberli

PROJECT OBJECTIVES

- To investigate whether the demise of the carbonate platforms in the Luconia province was influenced by the strengthening of the East Asian monsoon.
- To assess the relative importance of oceanographic factors, compared to sea level and tectonics, influencing the geometry and facies distribution of the platforms in the Luconia province.

PROJECT RATIONALE

For the past three decades, the morphology and reservoir distribution of the carbonates in the Luconia province has been discussed in terms of eustasy, tectonics, and clastic input (e.g. Epting, 1980; Vahrenkamp et al., 2004; Ting et al., 2011; Menier et al., 2014) while the impact of oceanographic changes in the South China Sea (SCS) is much less studied (Fig. 1). Although it has been hypothesized that waves, winds and ocean currents impacted the carbonate platforms, no clear mechanism was proposed (Gartner et al., 2004).

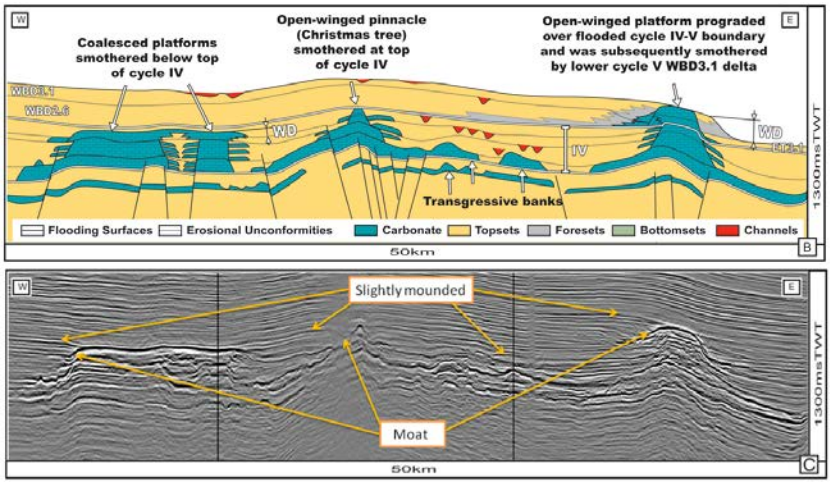

Figure 1. A semiregional section showing a range of carbonate-siliciclastic configurations characteristic of Central Luconia (Modified after Koša et al., 2015) (B) Schematic drawing of stratigraphic relationships interpreted in section by Koša et al., 2015 (C) Characteristics of seismic geometry that may be caused by ocean currents and aid in platform drowning.

There is increasing evidence that oceanographic changes, in particular the onset of strong ocean currents, have contributed to the drowning of platforms; for example, the Marion platforms (Eberli et al., 2010) and parts

of the Maldives (Betzler et al., 2009). Thus, we propose to evaluate if the oceanographic changes, which acted in concert with tectonic and sea-level changes, influenced the platform demise in the Luconia province.

SCOPE OF WORK

This research will focus on the Neogene environmental impact on Luconia carbonate platforms. To estimate the timing and causes of the drowning we will focus on the pre-, syn, and post-drowning strata by determining their ages and composition. Seismic 2D and 3D lines will be used to identify the seismic expression of current activities at the bounding surfaces. The onset of the current system and the platform demise will be studied by comparing the age of the platform drowning with the base of the basinal (drift) deposits and age will be constrained using available well and biostratigraphic data.

SIGNIFICANCE

Understanding the impact of the SCS paleoceanographic changes on the Luconia carbonate platform evolution will provide new insight on the drowning mechanism. Findings from this research can be applied to other carbonate platforms in the SCS region and potentially to many drowned isolated platforms. Furthermore, trends recognized in the sedimentary record of the Luconia province will shed light on the history of both the East Asian monsoon and the Western Pacific Warm Pool.

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DECIPHERING THE EVOLUTION OF THE NEW PROVIDENCE PLATFORM, BAHAMAS, USING 2D GPR DATA AND CORE CORRELATION

Emad H. Alothman, Mark Grasmueck, and Gregor P. Eberli

PROJECT OBJECTIVES

- Conduct a high-resolution sequence stratigraphic analysis of the Pleistocene carbonate deposits of New Providence Island on 250 MHz 2D GPR data.
- Integrate GPR data with outcrop facies analysis and high-resolution drone photography.
- Reconstruct the depositional history of the Tertiary deposits of New Providence Platform using a 670 ft core.

PROJECT RATIONALE

The carbonate deposits of New Providence Island, Bahamas, mainly formed during successive sea-level highstands (Reid, 2010). Detailed analysis of these deposits will be performed using 250 MHz 2D GPR data. This dataset shows high-resolution depositional sequences of the Pleistocene sea-level highstands from foreshore to eolianite deposits (Fig. 1). These deposits have proved to be faithful recorders of sea-level oscillations within sea-level highstands (Eberli, 2013; Jackson et al., 2013). For example, during MIS 5e, sea-level oscillated 10+ m, dividing the depositional sequence into early and late substages. In addition, smaller scale sea-level oscillations at the onset of glaciation produced extensive lateral accretion of downstepping beach ridges and associated subtidal deposits (Garret and Gould, 1984). These suborbital sedimentary cycles have major implications for cyclostratigraphy and how we extract high-frequency sea-level fluctuations from depositional cycles. The detailed documentation of depositional units produced by sea-level oscillations is thus of paramount importance.

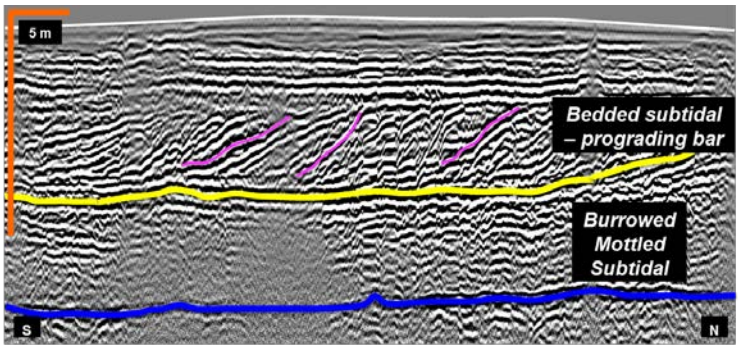

Figure 1. High resolution image from 2D GPR data showing subtidal foreshore and prograding bar deposits.

PROJECT DESCRIPTION

Pleistocene Sediment Analysis Using 2D GPR Data

The high resolution 250 MHz 2D GPR dataset provides a detailed view of the sedimentary successions of New Providence Island. This dataset will be essential in establishing a high-resolution sequence stratigraphic framework. The GPR dataset will serve as a guide to interpreting the sedimentary successions of the Pleistocene. High-resolution drone photography of the Clifton Pier area will be used for a visual perspective of the successions with respect to the GPR dataset. In addition, we plan to correlate the GPR data interpretations with sedimentary features observed in outcrop. This correlation will be done by visiting outcrops along road cuts and waterways that pass through the GPR data acquisition area.

Tertiary Sediments Analysis Using Core Data

The long-term evolution of New Providence Island will be analyzed in a 670 ft core, taken in the northern part of the island as part of the BahaMar Cooling Wells project (Fig. 2). Depositional and diagenetic facies analysis, using core interpretation and petrographic thin sections, will help decipher the depositional history of Tertiary deposits of New Providence Island. The core contains several dolomitic intervals and many exposure horizons that document the complex diagenetic history of these carbonates.

SIGNIFICANCE

Most of the sediments in the New Providence Platform were deposited in the Pleistocene. High resolution 2D GPR imaging will aid in understanding the depositional history of the sediments in more detail. The deeper sections of New Providence can be closely studied using the long core that is available.

Figure 2. Parts of the 670 ft core showing transition from light colored limestone to darker dolomite facies.

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CALCITE CONCRETIONS TO REFINE THE MARINE-TO-NONMARINE (SEQUENCE) BOUNDARY

Donald F. McNeill, James S. Klaus, and Peter K. Swart

PROJECT OBJECTIVES

- To use calcite concretions, a product of cementation by marine seawater, to better constrain the position of the marine-to-nonmarine deposition in a tropic mixed system.

PROJECT RATIONALE

Here we investigate the usefulness of calcite concretions to better identify and constrain the transition from marine sediments to non-marine sediments at the sequence boundary in a mixed system. We propose that calcite concretions with a stable isotope signature (-10 to -25 ‰ $\delta^{13}C$) that reflects bacterial sulfate reduction (BSR) and sometimes an isotopic signature of oxidation of methane (< -25‰ $\delta^{13}C$) are formed exclusively in the marine realm. When present, the distribution of concretions can be used across the lowstand-related deposits to refine placement of the actual sequence boundary. More specifically, the uppermost concretions better constrain the marine to nonmarine boundary. Similarly, during the subsequent transgression the lowermost concretions can help mark the transition of nonmarine to marine deposits where marine fossils are often absent.

SCOPE OF WORK

The Miocene-Pliocene mixed system of the Cibao Basin, Dominican Republic (DR) is a young, unconsolidated, undeformed shelf clinothem set. Our extensive work in the basin has identified several well-exposed sequence boundaries where concretions occur prior to subaerial exposure and fluvial deposition, as well as during the marine flooding at the end of exposure. The Yaque Group contains three depositional sequences (Cercado, Gurabo, Mao Fm.) where we will examine the isotopic composition of the calcite concretions and map their distribution across at least two sequence boundaries (one from falling sea level, one from rising

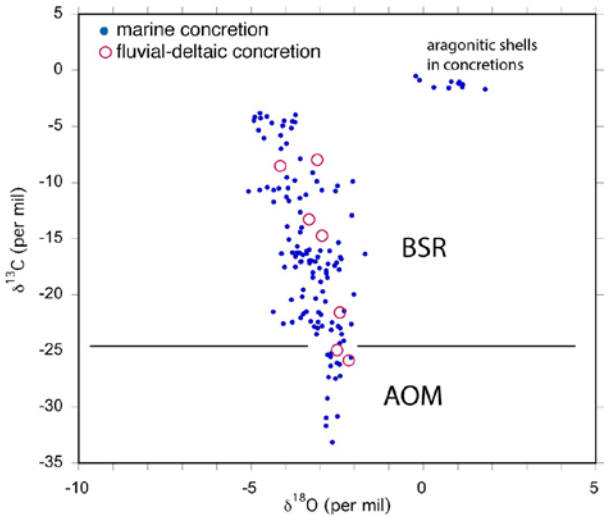

Figure 1. Crossplot of stable isotope data from calcite marine concretions (blue dots) and data from a concretion in the fluvial-deltaic sand and gravel (red circles) from the contact between Gurabo and Mao formations on Rio Cana.

sea level). We have tested one concretion at the sequence boundary between the Gurabo and Mao formations (Fig. 1). This test site has a series of calcite-cemented sand beds in the coarse gravel unit that overlies the marine silt lithofacies typical of the outer shelf. The lithified sand beds have calcite cements with carbon isotope values that range from outer edge values of -15‰ to center values of -25‰. These values are consistent with DR concretions formed under conditions of sulfate reduction. Sampling cemented beds across at least two sections that span a sequence boundary will test these initial results. The first section will be the transgression and shift from fluvial gravel to marine sands at the base of the Mao Formation. A second site (Fig. 2) will sample the section across the Gurabo Formation-Mao Formation sequence boundary at Rio Cana where marine deposits transition to sand and gravel beds and fluvial lithofacies.

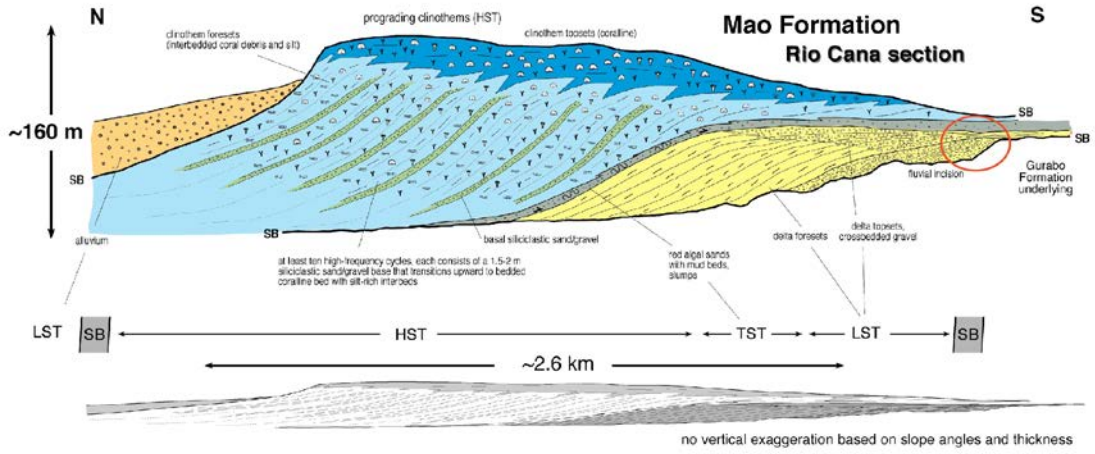

Figure 2. Schematic of the Mao Formation depositional package. This study will follow the occurrence of marine calcite concretions across the sequence boundary outcrop show by the red circle at the base of the Mao Formation. The initial data shown in Figure 1 indicates that concretions can form in the fluvial-deltaic deposits during the fall of sea level and eventual exposure. This project will characterize the nature of cementation across the boundary to test our hypothesis.

DELIVERABLE PRODUCT

This study is a proof-of-concept to evaluate the potential to use marine concretions, in circumstance where they occur, to provide a means of refinement to the boundary between marine and nonmarine lithofacies. Where concretions occur, especially in the mixed system, they may be reliable markers of the change from, or to, marine deposition.

DECONSTRUCTING THE SEDIMENTOLOGY OF MIXED CARBONATE-SILICICLASTIC DEPOSITION: CIBAO BASIN, DOMINICAN REPUBLIC

Brandon Burke, James S. Klaus, Donald F. McNeill, and
Peter K. Swart

PROJECT OBJECTIVES

- Provide a textural, geochemical, and paleo-ecological calibration of an outcrop section through an unconformity-bounded mixed system sequence.
- Develop a depositional model for tropical mixed skeletal (reef) and mud- sourced deposition that includes the timing of siliciclastic inputs and variability in carbonate production.
- Assess the magnitude of the late Miocene Zanclean transgression and compare the mixed systems response to other global signatures from this event.

PROJECT RATIONALE

The diverse settings in which carbonates and siliciclastics mix provides a challenge in developing predictive models of lithofacies distribution and geobody geometry. The primary goal of this project is to provide a textural, geochemical, and paleoecological calibration of a newly discovered outcrop section through a unconformity-bounded clinothem package. The Gurabo Formation of the Cibao Basin in the Dominican Republic is late Miocene and early Pliocene in age and forms one of the best examples of low-latitude margin progradation in a mixed system setting (McNeill et al., 2012). The new outcrop section vertically transects the middle part of the depositional sigmoid and records the sedimentologic and stratigraphic archive

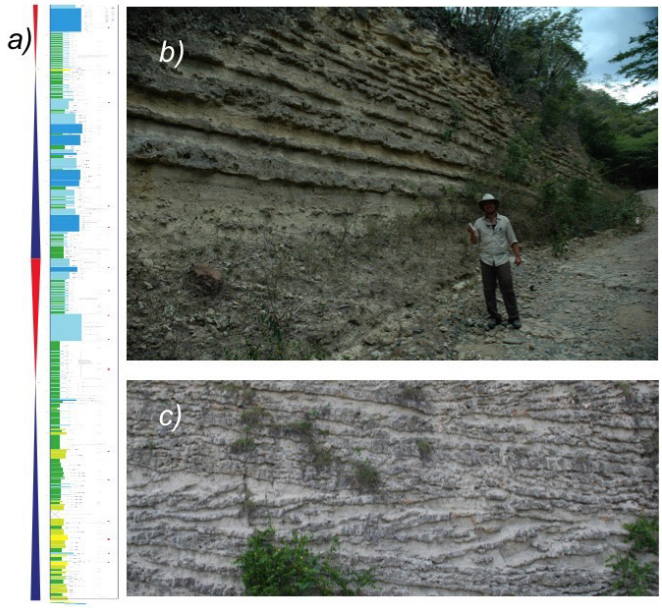

Figure 1. a) Stratigraphic column for Gurabo section.

b) Outcrop exists between 68 m to 80 m in stratigraphic section.

c) Stratigraphy within the Rio Mao terraced section, 93 m to 102 m in section.

of deposition during and after a major global transgression (the Zanclean Flood near the Miocene-Pliocene boundary and the early Pliocene highstand). These deposits are unusual in being largely unconsolidated and amenable to sedimentologic characterization; providing an ideal outcrop analog for tropical mixed system deposition on the shelf margin.

The resultant sequence "ground truthing" will be used to refine a depositional model for tropical mixed skeletal and mud-sourced deposition. The data generated from this section can be used to forward model the development of potential reservoir beds in a conventional (vuggy carbonates) and unconventional (mud rich) framework.

SCOPE OF WORK

During the first phase of this project we measured a 178 m thick section, with some additional outcrop still remaining above our top level, but below the upper sequence boundary. Lithologic and biostratigraphic samples were collected at ~1 m intervals with a small gasoline-powered rock drill. The drill enabled rapid collection of fresh material away from the weathered outcrop surface. These samples will be used for mineralogy (XRD), total organic carbon analysis, bulk stable isotopic composition (P.K. Swart, SIL), determination of benthic and planktic foraminifera (B. Lutz, Shell), calcareous nannofossil stratigraphy (R. da Gamma, Shell), and grain size and compositional analysis. In addition, we will collect the key coral fauna in the transect for two purposes: water depth and possible aragonite samples for radiometric age dating (U/Pb, J. Woodhead, U. Melbourne). The benthic and planktic foraminifera provide integrated water depth, upwelling, and age constraints for the section.

SIGNIFICANCE

The expected results of this research will provide a calibrated lithofacies section that penetrates the thickest part of the margin sigmoid, and will resemble data that might be recovered in a core or borehole log. Regionally, this calibration will provide a new, additional record of the nature of carbonate and siliciclastic mixing in a mud-rich, tropical shelf margin. Globally, this section records the magnitude of the Zanclean transgression. This global transgression is recorded in seismic profiles and cores from several locations around the world (Gulf of Papua shelf margin, Belize shelf, isolated platforms in the South China Sea, and the Great Barrier Reef in Northern Australia) and will be further refined (Tcherepanov, 2008).

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PETROPHYSICAL PROPERTIES OF A FRINGING REEF MARGIN

Pierre Casco, Viviana Diaz, James S. Klaus, Donald F. McNeill, Albertus Ditya, Ralf J. Weger, and Gregor P. Eberli

PROJECT OBJECTIVES

- Determine the petrophysical properties (electrical resistivity, ultrasonic velocity, porosity, permeability, and density) within a seven borehole transect across the Pleistocene reefal carbonates of the southern Dominican Republic.
- Assess the relative influence of primary depositional facies and subsequent diagenetic alteration on the measured mechanical and petrophysical properties.
- Develop a gridded model from core measurement and stratigraphic data that can be used to assess optimal seismic acquisition parameters and limits of imaging resolution within the reefal margin.

PROJECT RATIONALE

Understanding controls on the petrophysical properties of carbonates is often key to proper interpretation of reservoir properties (porosity, permeability) from either seismic or well-log data. Petrophysical properties of carbonate sediments exhibit considerable spatial heterogeneity based on grain size, texture, and packing. Furthermore, diagenesis alters the original fabric and rock properties shortly after deposition due to changes in mineralogy and inversion of pore distribution.

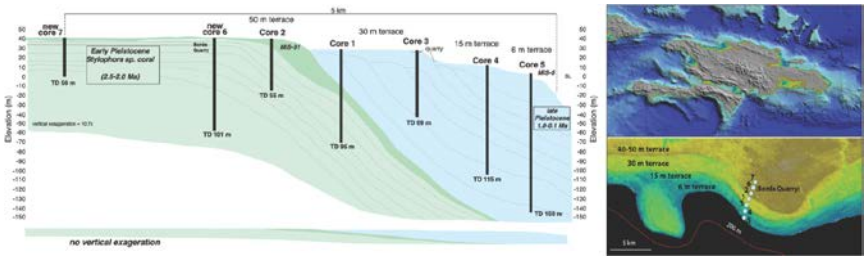

Figure 1. Cross-sectional model of Pliocene to Pleistocene reef sigmoids on the southern coast of the Dominican Republic based on seven drilled boreholes.

The objective of this project is to complete a comprehensive characterization of the mechanical and petrophysical properties of the Pleistocene reefal carbonates of the southern Dominican Republic. Following the initial drilling phase of the Dominican Republic Drilling Project in 2010, a total of 170 plug samples were analyzed for mechanical and petrophysical properties. These samples were collected at a maximum depth of ~60 m, and represented primarily by shallow water depositional facies heavily impacted by meteoric diagenesis. In 2012 a second phase of drilling added new deep wells in both younger and older strata, and extended existing wells to recover the deeper water forereef facies.

SCOPE OF WORK

Since the initial drilling of the Dominican Republic cores we have been working to develop a temporally constrained sequence stratigraphic model for the seven core transect through the Pleistocene reef deposits. Age determinations were based on biostratigraphic markers, strontium isotopes, magnetostratigraphy, and radiometric dating. A revised depositional model constrains the prograding reef system of the southern Dominican Republic to between 1.6 and 0.125 Ma. Once dated, these cores were used to assess accretion and progradation rates, and reconstruct fringing reef zonation and facies geometries both vertically and perpendicular to the coast.

In addition to the previously sampled cores, 87 additional one-inch diameter cylindrical plugs of variable length were drilled for petrophysical measurements. Plugs were sampled from the cores using a water-cooled diamond drill bit with vertical and horizontal orientation. The ends of the plugs were cut off and then polished to within 0.01 mm precision (measured with a micrometer gauge) to create a flat surface for optimizing contact area between sample and sonic or electric transducers. Samples were dried at 60^{o}C for 48 hours and then stored in a desiccator for approximately 24 hours. The dry-mass of the samples was measured to the microgram using a Thomas Scientific T200S electronic scale. Chips from one end of each plug were sent to the University of Iowa's Geology Department for thin section preparation.

Petrophysical measurements will include electrical resistivity, ultrasonic velocity, porosity, permeability, and density. The petrophysical properties will be compared to assess their relationship to each other and for external comparison, for instance: porosity-permeability, porosity-acoustic velocity. The petrophysical properties will then be analyzed based on petrographic observations in order to assess a correlation between petrophysical properties and depositional/diagenetic environments.

EXPECTED RESULTS

The dataset of petrophysical properties will be coupled to geologic parameters:

- Age
- Platform morphology (isolated, shelf, and ramp)
- Climate zone (tropical, cool-water, temperate)
- Depositional environment (top, shoal, slope, basin)
- Type of information (outcrop, subsurface)
- Texture (Dunham)
- Dominant pore type and microporosity
- Sequence stratigraphic position
- Mineralogy

The resulting dataset will be compiled with other well-studied projects to provide an unprecedented catalogue of sample set information with interconnected relationships (See Schnyder et al. this volume).

ASSEMBLE COMPREHENSIVE DATABASE OF MECHANICAL AND PETROPHYSICAL PROPERTIES OF PLATFORM CARBONATES

Jara S.D. Schnyder, Gregor P. Eberli, Donald F. McNeill, and Ralf J. Weger

PROJECT OBJECTIVES

- Assemble mechanical properties (velocity, density, elastic moduli) and petrophysical properties (porosity, permeability, resistivity) of carbonate platforms and their adjacent basinal sediments.
- Organize data set according to age, setting, environment, texture, dominant pore type, and mineralogy for the evaluation of interconnected relationships.

PROJECT RATIONALE

Mechanical and petrophysical properties of carbonates strongly depend on facies, depositional lithology, and diagenetic alteration. Last year we constrained parameter ranges of elastic properties calculated based on density, v_p, and v_s velocity for Ocean Drilling Program Site 1007 (ODP Leg 166), CLINO, and UNDA on Great Bahama Bank (GBB), from platform top to the toe of slope. This data set was intended to provide realistic input parameters for fracture generation models or structural restoration. Because the Bahamas data set is most applicable for Tertiary tropical platforms but not necessarily exemplary for other carbonate systems, we expand the project to other platforms from different ages and settings. In addition, in this year's project we expand the auxiliary information such as platform morphology, age, carbonate factory, and others. A comprehensive overview of relationships and trends of mechanical and petrophysical properties within a geologic context is paramount for various types of modeling.

DATA BASE

The vast CSL database, assembled during petrophysical studies over the past decades includes approximately 30,000 samples from unconsolidated sediment to Paleozoic limestones and dolomites (Fig. 1). These include amongst others:

- Tertiary sub-tropical carbonates (Marion Platforms, off Australia)
- Tertiary tropical carbonates (Maldives, Bahamas, Florida, Dominican Republic)
- Cretaceous carbonates from the Middle East from three large oil fields
- Cretaceous platform carbonates (Maiella Platform – Italy)
- Jurassic-Cretaceous carbonate ramp (Neuquén Basin – Argentina)
- Permian ooid shoals (Khuff Formation)
- Carboniferous (Pennsylvanian) shelf (Paradox Formation - Utah)
- Carboniferous (Mississippian) ramp (Madison Formation – Wyoming)
- Devonian isolated platforms (Miette and Ancient Wall – Canada)

- Microbialites (modern Hamelin Pool/Bahamian and Miocene stromatolites, travertine and tufa).

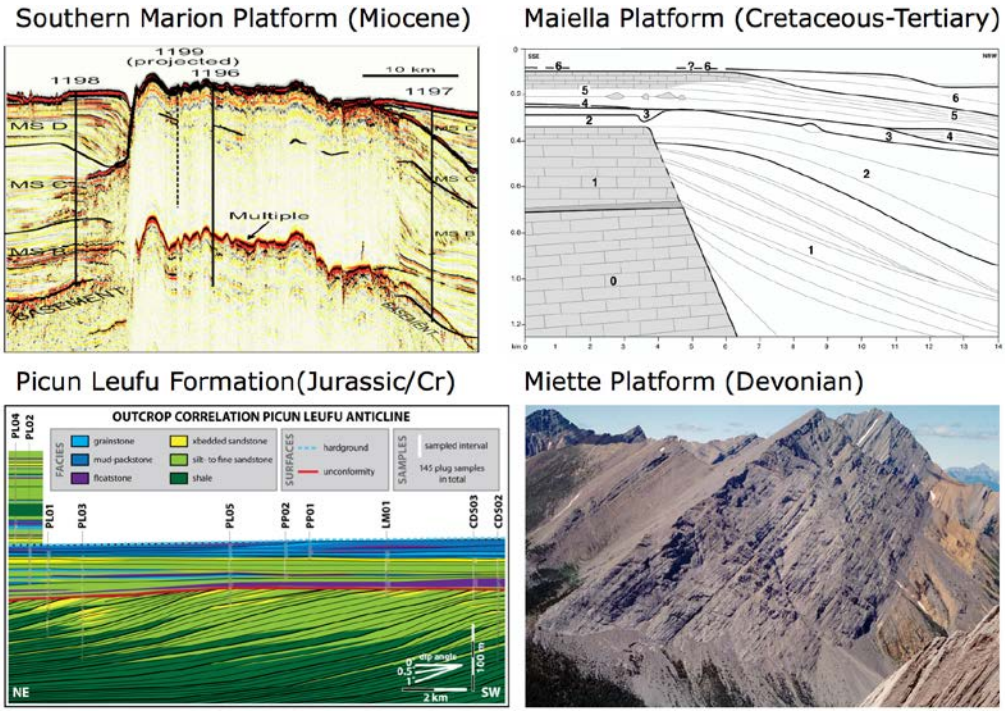

Figure 1. Four different platform settings of different age out of the CSL database: Seismic line through Southern Marion Platform (Miocene) in offshore NE Australia; interpretation and stratigraphic sequences for Maiella Platform (Cretaceous/Tertiary) in Italy, outcrop correlation of Picun Leufu Formation (Jurassic) in Argentina, and Miette Platform (Devonian) in Canada.

PROJECT DESCRIPTION

The mechanical and petrophysical properties (density, velocity, resulting elastic moduli, resistivity, porosity, and permeability) will be extracted from the CSL database. These properties will be coupled to the geological parameters that will allow the user to search for interconnected relationships. These parameters include:

- Age
- Platform morphology (isolated, shelf, and ramp)
- Climate zone (tropical, cool-water, temperate)
- Depositional environment (top, shoal, slope, basin)
- Type of information (outcrop, subsurface)
- Texture (Dunham)
- Dominant pore type & microporosity
- Sequence stratigraphic position
- Mineralogy

EXPECTED RESULTS

The result is an unprecedented catalogue of sample set information with interconnected relationships. This will facilitate studies on geotechnical and petrophysical aspects of carbonate environments in a wide range of settings and ages.

PROJECTS FROM IODP EXPEDITION 359 - MALDIVES PLATFORM AND CURRENT DEPOSITS (YEAR 2)

Gregor P. Eberli, Peter K. Swart, Anna H.M. Ling, Emma Giddens, Christian Betzler[1], and Thomas Lüdmann[1]

2) CEN, University of Hamburg, Germany

MAIN PROJECTS OF IODP 359 POST-CRUISE RESEARCH AT THE CSL

- Document the drowning of carbonate platforms in the transition from sea-level controlled to current dominated sedimentation in the Maldives carbonate system.
- Comprehensively describe the hitherto unknown carbonate contourite fan in the Kardiva Channel.
- Give new insights into the formation of secondary porosity in the marine realm.
- Test the Extended Biot Theory in carbonates.

359 EXPEDITION OVERVIEW

The International Ocean Discovery Program (IODP) Expedition 359 drilled, cored, and logged at 8 sites in the carbonate edifice of the Maldives, located in the Indian Ocean (Fig. 1). Expedition 359 had two main focus points. The first was to date the onset of the current system that is potentially in concert with the intensification of the Indian monsoon and the initiation of the modern current system in the world's ocean (Betzler et al., 2016a). The second important outcome of Expedition 359 is documentation of the dramatic change in the style of the sedimentary carbonate sequence stacking, caused by a combination of relative sea-level fluctuations and ocean current changes (Betzler et al., 2016b). The Preliminary Report summarizing the results is available online http://publications.iodp.org/preliminary_report/359/.

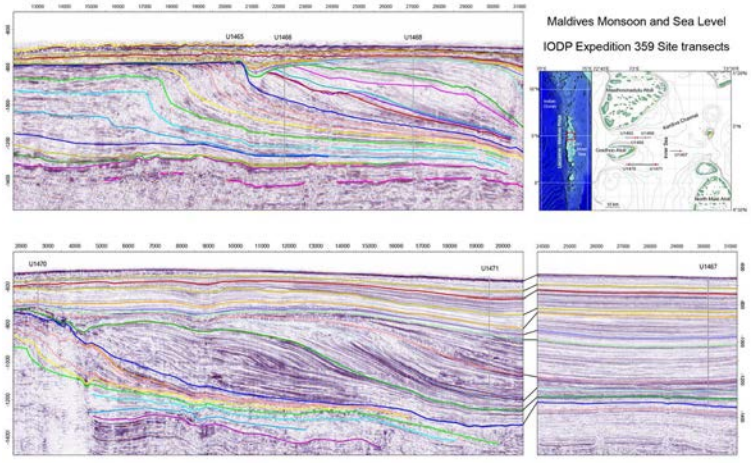

Figure 1. Seismic lines and location map of the two transects drilled during IODP Expedition 359 to the Maldives.

SIGNIFICANCE

The findings from Expedition 359 and the planned post-cruise research will add significant new knowledge with regards to the generation of organic-rich strata in shallow carbonate environments and the interaction between currents and platform evolution. The discovery of coarse-grained carbonate drift deposits, which had previously been interpreted as a sea-level driven downstepping platform (Belopolsky and Droxler, 2004), is the equivalent of finding a new carbonate depositional system. Similarly, the discovery of generating secondary porosity through the dissolution of celestine is a new diagenetic process, the importance of which was previously unrecognized. Together these findings improve our knowledge of sedimentologic and diagenetic processes in the carbonate environment. These findings will be clearly applicable to other Tertiary carbonate platforms in the Indo-Pacific region and to numerous others throughout the geological record.

SCOPE OF POST-CRUISE WORK

In April 2016, the scientists of Expedition 359, including the three cruise participants from the CSL (Swart, Eberli, Ling), gathered at the IODP core repository at Texas A&M to sample the 3096 m cores for post-cruise research. These samples and the high-resolution XRF data of the cores will complement all the data produced on board that includes lithologic descriptions, biostratigraphy, vast amounts of geochemical and petrophysical data as well as logs. This formidable data set is used for five follow-up projects within the CSL, some in collaboration with other scientists. Each one is described in detail in the following pages. They revolve around three topics:

1. The interplay of sea level and currents in controlling the architecture and demise of carbonate platforms.
2. The sedimentologic description and the petrophysical calibration of the discovered coarse grained carbonate drift fan.
3. The generation of organic-rich strata and other diagenetic processes in these strata.

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PETROPHYSICAL CALIBRATION OF THE COARSE-GRAINED CARBONATE DRIFT FAN, MALDIVES

Emma Giddens, Gregor P. Eberli, Luuk Kleipool[3], Ralf J. Weger, Christian Betzler[1], Thomas Lüdmann[1], and Angela Slagle[2]

1) CEN, University of Hamburg
2) Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY
3) Shell Global Solutions International, Rijswijk, The Netherlands

PROJECT OBJECTIVES

- Describe the carbonate drift fan in the Kardiva Channel: sedimentology, petrophysics, and seismic signature.
- Measure porosity, permeability, velocity, and resistivity and relate properties to facies, diagenesis, and pore structure of each plug.
- Correlate lithology and petrophysical properties to logs and seismic data for a thorough calibration of the seismic and log facies of the drift fan.
- Compare geometry and sedimentology and petrophysics of this drift fan with a Cretaceous drift fan in the Maiella Mountains.

PROJECT RATIONALE

One of the discoveries of IODP Expedition 359 to the Maldives was that current deposits in the Kardiva Channel form a drift fan (Fig. 1). Although the drift package in the channel was identified based on geometries seen on the seismic data (Lüdmann et al., 2013), the cores revealed a facies evolution that has far-reaching implications for interpretations of neritic carbonates. No such system has been reported for carbonates before. Thus, a comprehensive documentation of lithology, seismic and log facies, as well as diagenesis and petrophysical properties of the drift fan is needed. This effort had started with the documentation of the sedimentology and seismic facies by Thomas Lüdmann on behalf of the entire scientific party.

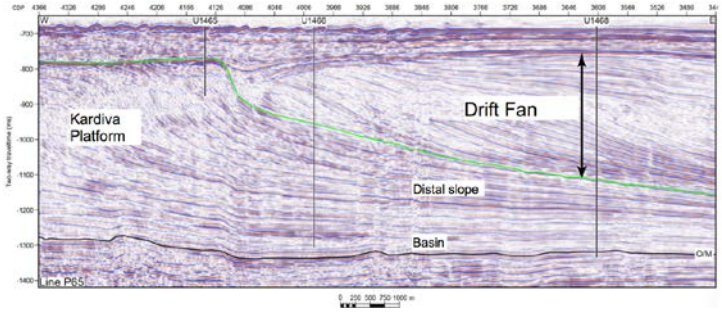

Figure 1. Seismic image of the coarse-grained drift fan in the Kardiva Channel that is a unique sedimentary system that has not been described in the literature.

SCOPE OF WORK

The sedimentologic description of the contourite fan will be accomplished with a publication based on shipboard data by Thomas Lüdmann. The

correlation to log and seismic data will be focus of a follow-up study. The necessary laboratory calibrations of the petrophysical properties will be performed in Miami. For the petrophysical characterization of the contourite fan, we will measure porosity, permeability, velocity, and resistivity. Velocity and resistivity measurements will be conducted under variable pressure conditions to simulate the burial depth of the samples. This data set will be compared to the log data and both will be correlated to the lithologic and seismic facies. The data set will also be compared to the petrophysical characteristics of the drift deposits on the Marion Plateau where laboratory measurements and log data already exist (Ehrenberg et al., 2004; Eberli et al., 2010).

In addition to the laboratory measurements, we will investigate the pore structure with digital image analysis (DIA). The DIA is able to quantify the pore structure that influences both velocity and resistivity variations at any given porosity.

The high porosity of up to 60% in these deposits indicates secondary porosity development. In a related study, the role of the celestine formation and dissolution will be investigated as an important process affecting the occlusion and preservation of porosity (see Swart et al., this volume).

The drift fan has geometries and sedimentologic characteristics similar to those of the Cretaceous Orfento Formation in the Maiella Mountains that has been studied in detail, but for which several depositional models have been proposed (Mutti et al., 1996; Vecsei 1998). It is our working hypothesis that these Cretaceous coarse-grained deposits are also a drift fan.

SIGNIFICANCE

The documentation of this coarse-grained drift fan in carbonates will have major implications for carbonate sedimentology. It is a new sedimentary system that has not been described before. The comprehensive documentation of this carbonate contourite fan will prompt the re-interpretation of deposits, such as neritic shoals or prograding delta lobes. The coarse nature and the high porosity make the deposits potentially an important reservoir facies.

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INFLUENCE OF OCEAN CURRENTS ON MIOCENE CARBONATE PLATFORM DROWNING

Anna H.M. Ling, Gregor P. Eberli, Christian Betzler[1], and
IODP Expedition 359 Scientists
4) CEN, University of Hamburg, Germany

PROJECT OBJECTIVE

- Test the hypothesis that ocean currents are a major contributor towards carbonate platform drowning at the Kardiva Carbonate Platform, Maldives and Miami Terrace, Florida, USA.

PROJECT RATIONALE

Carbonate platform drowning is a common phenomenon in the carbonate system for which many theories exist such as global anoxic events, fast sea-level rise, tectonic break-up, and nutrient excess (Hallock and Schlager, 1986). However, evidence also exists for the close relationship between platform drowning and intensification of ocean currents, for example, for the Miocene platforms on the Marion Plateau (John and Mutti, 2005; Eberli et al., 2010). Likewise, Betzler et al. (2013) proposed that in the Maldives the onset of monsoon-related currents correlate with the drowning of the platforms. Similarly, Mullins and Neumann (1979) proposed that the intensification of the Florida Current may have been responsible for the cessation of growth at the carbonate platform forming the Miami Terrace. All of these examples make it necessary to test if platform drowning is related to ocean currents.

APPROACH

The hypothesis that platform drowning is related to ocean currents will be tested by performing the following tasks:

1) Assess the coeval onset of the current system with the platform demise by comparing the age and sediment facies of the platform drowning with the base of the drift deposits (Fig. 1). 2) Perform geochemical analyses on proxies of water mass changes with the onset of the current system in the basinal drift deposits and the drowning succession on the platform top.

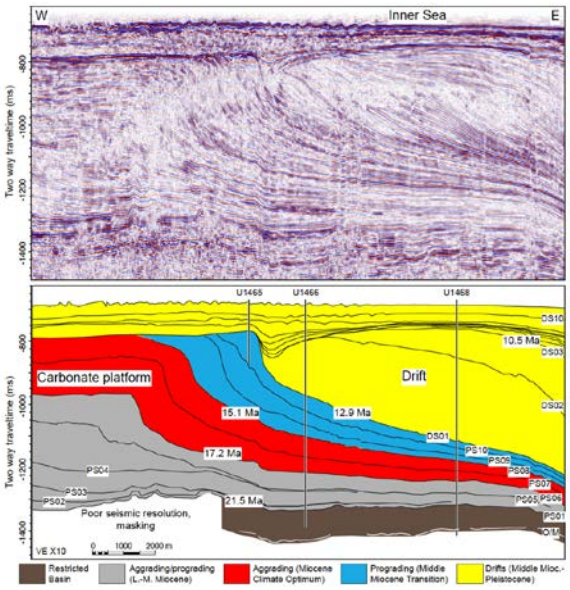

Figure 1: Seismic line and interpretation of the physical relationship between platform growth (blue) and drift deposition (yellow) (Betzler et al., 2016).

DATA SETS

Relevant datasets from IODP Expedition 359 consist of lithostratigraphic data, geochemical data, petrophysical data, and biostratigraphic data while datasets from the Miami Terrace are seafloor dredge samples consisting of phosphatic limestones. Sr-isotope dating will be conducted to assess the onset of current activity at the platform. Geochemical proxies for nutrient enrichment such as Cadmium (Cd), Barium (Ba), Phosphate (PO_4^{3-}) and Nitrate (NO_3^-) in the slope and the drift deposits will test if there is a lead or lag of nutrient enrichment at the time when the platform drowned. Evidence for potential nutrient influx onto the platform by current activity can be identified based on the changes in biota. The increase in nutrients would change the reef-dominated platform into an algal dominated platform.

SIGNIFICANCE

This study is significant in providing insights regarding the process of carbonate platform drowning. If the relationship can be established within the Miocene platforms in the Maldives and Florida, this process which appears to be connected with the demise of carbonate platforms can be applied (or tested) in ancient carbonate platforms. If drowned carbonate platforms are current recorders, there is a possibility of reconstructing paleo-current onsets with major drowning events throughout the geological record, in particular for pre-Mesozoic times when the oceanic sediments are not preserved.

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THE FORMATION OF CELESTINE: A POSSIBLE MECHANISM FOR THE CREATION OF POROSITY IN PLATFORM DERIVED SEDIMENTS

Peter K. Swart, Greta J. Mackenzie, and Gregor P. Eberli

PROJECT OBJECTIVES

- To understand the importance of celestine formation on the occlusion and preservation of porosity.
- To understand the influence of celestine upon the pore water geochemistry during and subsequent to its formation.

PROJECT RATIONALE

Celestine (often referred to as celestite) is a common mineral formed during marine burial diagenesis as the Sr, which is more abundant in biogenic carbonates, is excluded during neomorphism and recrystallization. Celestine saturation is common in the deep-sea record and about 10% of all sediments cored by the Ocean Drilling Program-International Ocean Discovery Program (OPD-IODP) attain saturation with respect to this mineral (Hoareau et al., 2010). Celestine is also common throughout the geological record (Hanor, 2004) and in some instances forms large concretions, often replaced by calcite, up to one meter in diameter (Yan and Carlson, 2003). While celestine is also known in other depositional environments, such as coastal carbonates and evaporites (Hanor, 2004; Taberner et al., 2002), the origin of these occurrences is uncertain.

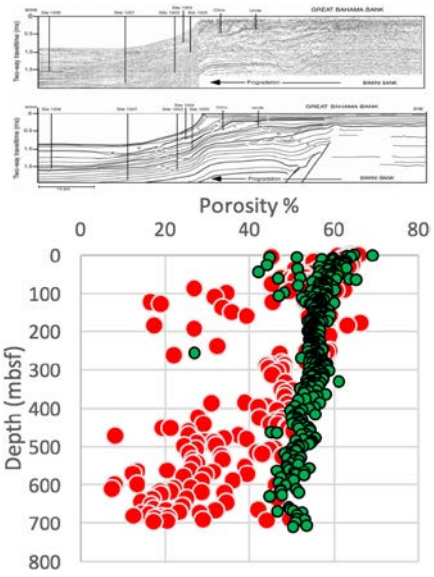

Fig. 1: Transect of sites off the western margin of Great Bahama Bank (upper panel). Changes in porosity from Sites 1006 (green) and 1005 (red) (lower panel).

The formation and occlusion of porosity in sediments deposited along the margins of carbonate platforms is an important process in controlling the hydrocarbon potential of a reservoir. However, the processes governing the development of porosity in carbonate reservoirs are poorly understood and frequently large variations occur without an obvious explanation. A particularly good example of this can be found in the changes in porosity that take place at two sites adjacent to the Great Bahama Bank (GBB) (Fig. 1). Site 1006, the site furthest away from the margin of GBB, shows the decrease in porosity anticipated as a result of compaction, while Site 1005, located 20 km closer to the platform, shows large erratic variations in porosity normally ascribed to carbonate diagenesis (dissolution

of primary carbonate components and their replacement by cement). In the proposed work we will investigate a new process we believe to be important in controlling porosity development in marginal sediments deposited adjacent to carbonate platforms.

SCOPE OF WORK

We will analyze samples collected during IODP Expedition 359 to the Maldives and from Site 1005 (ODP Leg 166). Expedition 359 drilled eight sites adjacent to atolls in the Maldives and penetrated up to 1000 m below the sea floor reaching sediments of late-Oligocene age. These sites were located close to Site 716 drilled during ODP Leg 115 where celestine was detected. During Exp 359, celestine was detected using X-ray diffraction at four of the sites cored; U1466, 1467, 1468, and 1471. The greatest abundance of celestine was measured at Site U1471, although since samples were only analyzed every ~9 m celestine may be more prevalent than recorded.

SIGNIFICANCE

The occurrence of celestine, while well known, has been mainly regarded as a curiosity. This study will be the first to recognize its potential as a major and important creator of porosity. We propose that this mineral forms early in the paragenetic sequence, filling porosity and thus preventing sediments from becoming compacted and filled with carbonate cement. Once the surrounding carbonate sediments become lithified and the sediment is buried below the zone of super saturated pore waters, the celestine dissolves and the porosity of the rock becomes available once more. Furthermore, this process occurs preferentially in sediments derived from aragonite precursors and therefore should be more prevalent in sediments that formed during aragonite seas.

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TESTING THE EXTENDED BIOT THEORY IN CARBONATES OF THE MALDIVES

Ralf J. Weger, Emma Giddens, Gregor P. Eberli, Christian Betzler[1], Thomas Lüdmann[1], and Angela Slagle[2]

1) CEN, University of Hamburg

2) Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY

PROJECT OBJECTIVES

- Test the Extended Biot Theory on core and logs from IODP Site U1467 by:
  - Calculating the pore shape parameter γ_k from laboratory measurements of porosity and p-wave and shear wave velocity.
  - Assessing the pore structure with digital image analysis and relating it to the theoretical pore shape parameter γ_k.
  - Correlating γ_k to permeability.

PROJECT RATIONALE

The Extended Biot Theory captures theoretical pore structure variations in a term called γ_k, which uniquely quantifies velocity variations at a given porosity (Fig. 1; Sun, 1994; Weger, 2006). Other theoretical equations of poro-elasticity do not account for pore structure and thus produce large uncertainties when relating porosity to velocity in carbonates. Because the pore shape factor is directly linked to the pore structure, it links sonic velocity to permeability. Laboratory measurements of discrete samples have shown that γ_k indeed relates to the pore structure (Weger, 2006). The next step is to test the Extended Biot Theory with core and log data. During IODP Expedition 359 in the Maldives, the necessary data set was acquired for such a test. At Site U1467, a continuous core through highly porous carbonates was recovered and the logs included a DSI (dipole shear imager) sonic log that measures both compressional and shear waves as needed to test the Extended Biot Theory in core and logs.

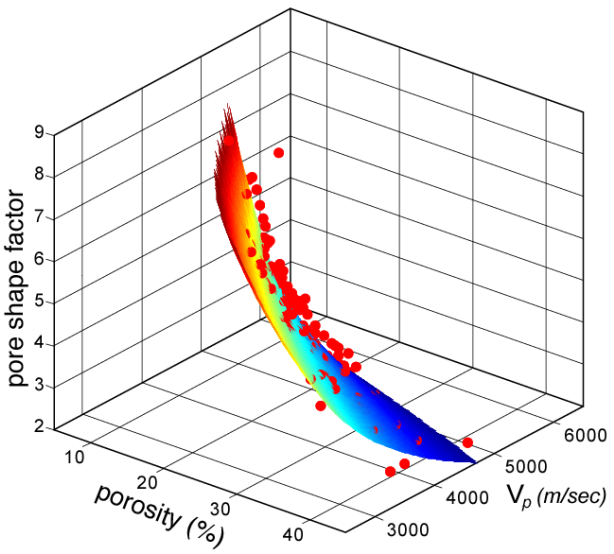

Figure 1. 3-D plot of velocity-porosity and γ_K. Red dots are measured samples. The colored surface is a theoretical surface of γ_K values formed by all possible velocity-porosity combinations for water saturated calcite at a given Vp-Vs ratio.

SCOPE OF WORK

At Site U1467 all the data are in hand to test the Extended Biot Theory (Fig. 2). The log data (P and S-waves, density, and porosity) will be used to calculate the theoretical pore shape parameter γ_k. We will measure the acoustic properties in the laboratory on discrete samples and calculate γ_k. Thin sections from the plug samples will be used to determine the pore structure with digital image analysis (DIA) in a workflow described by Weger et al. (2009). The test will be positive if γ_k correlates to permeability.

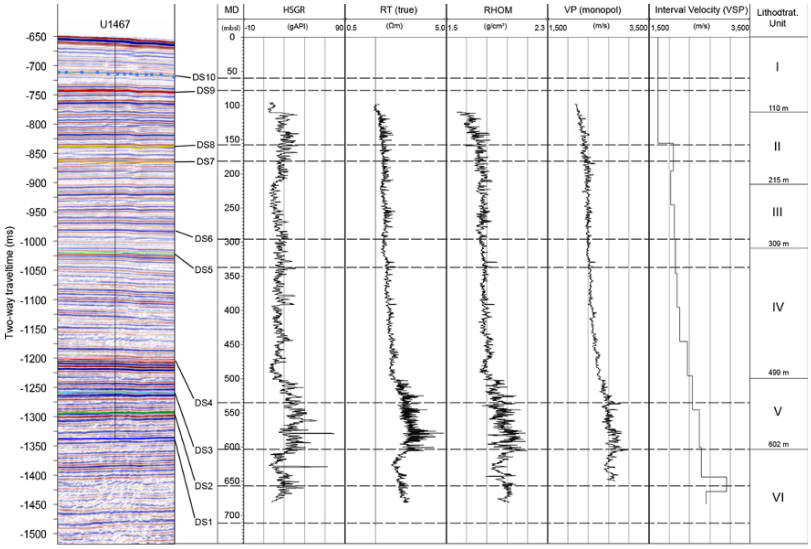

Figure 2. Seismic data of IODP Site U1467 and the corresponding logs allowing the Extended Biot Theory to be tested in carbonates (from Betzler et al., 2016).

SIGNIFICANCE

The Extended Biot Theory captures the pore structure using acoustic properties and therefore relates acoustic to hydraulic properties, which can potentially help to estimate permeability from seismic data. Because γ_k is derived from theoretical equations it can be calculated from acoustic data like a seismic attribute.

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THE ORIGIN OF ORGANIC RICH LAYERS IN THE MALDIVES

Peter K. Swart, Christian Betzler, Gregor P. Eberli, and the Shipboard Party of IODP Expedition 359

PROJECT OBJECTIVES

- To understand the origin of organic-rich layers, some containing over 5% organic material, alternating with organic poor layers within an 80m thick interval in a shallow, open ocean setting.

PROJECT RATIONALE

During the drilling of International Ocean Discovery Program (IODP) Expedition 359 seven sites were drilled in the Maldives (Betzler et al., 2016). At Sites U1466 and U1468 approximately 80 m thick intervals were encountered, comprised of alternating black and white layers (Fig. 1) in upper Oligocene to lower Miocene strata above neritic carbonates with large benthic foraminifers. The black layers contained total organic carbon contents of between 1 to 5 wt %, while the white layers had less than 0.1% organic material and were rich in calcareous nanofossils. The black layers were also enriched in trace elements (such as Fe, V, U, Mo etc.), which are typically associated with organic-rich sapropelic-like sediments. The important question raised by this unusual occurrence of organic-rich sediments is whether they (i) represent a preservation signal resulting from anoxic bottom waters, or (ii) a production signal arising from high surface productivity.

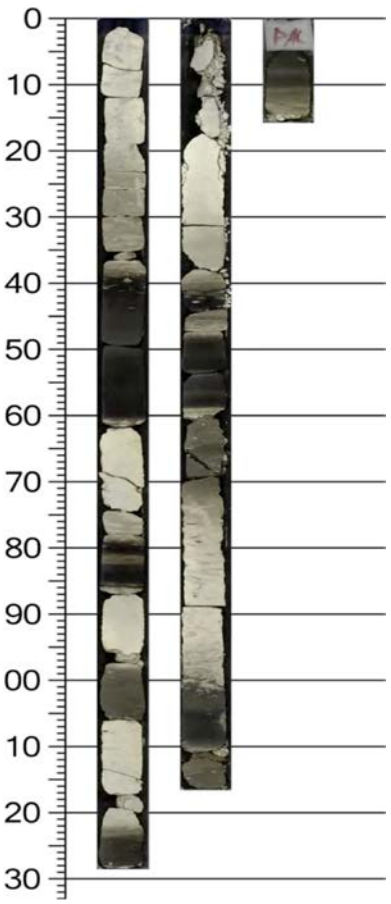

Figure 1: Sections from 359-U1466B-56R showing early Miocene intervals of organic-rich sediments interspersed with white coccolith-rich chalky oozes.

SCOPE OF WORK

In order to answer the above-mentioned question, we have been conducting a detailed study of the organic carbon content combined with analysis of the $\delta^{13}C$, $\delta^{15}N$ and C/N ratio and high resolution X-Ray fluorescence scans of the cores. Preliminary data indicate little change in the $\delta^{13}C$ value of the organic material, which could indicate variations in the

source during this period. In addition, the $\delta^{15}N$ values are close to 0‰, suggesting an absence of upwelling as a control on the supply of nutrients (an upwelling source would possess a high $\delta^{15}N$ value) and therefore productivity. Hence available data suggest a constant production of organic material in the surface water combined with periodic restriction of the bottom waters inducing anoxia.

Seismic data indicates that during the formation of these organic-rich layers the archipelago of the Maldives was not yet rimmed by large atolls but was a shallow basin. The Maldives archipelago was at the time still south of the equator in the middle of the Indian Ocean. It is possible that a shallow sill depth between the shallow basin and the open ocean periodically led to stagnant anoxic bottom waters as sea-level oscillated.

SIGNIFICANCE

The significance of our findings is that source rocks can form in open oceanic atoll-like systems, given the appropriate oceanic conditions and restrictions of water input. Provided that an adequate seal is present, such systems may actually be important in forming hydrocarbons as there is a combination of a good source material underneath a porous reservoir.

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THE VACA MUERTA RESEARCH INITIATIVE (YEAR 3): NEUQUÉN BASIN, ARGENTINA

Vaca Muerta Team of the CSL – Center for Carbonate Research

INITIATIVE OBJECTIVES

- Produce outcrop analogs for the Vaca Muerta Formation in the Neuquén Basin in the proximal to the distal portion of the basin.
- Use lithological, geochemical, and petrophysical properties of the Vaca Muerta Formation to advance knowledge of the accumulation, preservation, and distribution of organic-rich mudstones.
- Conduct individual projects for a comprehensive assessment of the sedimentologic, geochemical, and stratigraphic processes in this and other unconventional plays.

RATIONALE AND BACKGROUND

The U. Jurassic - L. Cretaceous Vaca Muerta Formation in the Neuquén Basin, Argentina, has enormous unconventional resource potential. The excellent exposure of the formation from the proximal to the distal portion of the basin offers the unique opportunity to address fundamental questions about the distribution of total organic carbon (TOC), geo-mechanical properties of the various facies, and the factors controlling these variables in this and other basins.

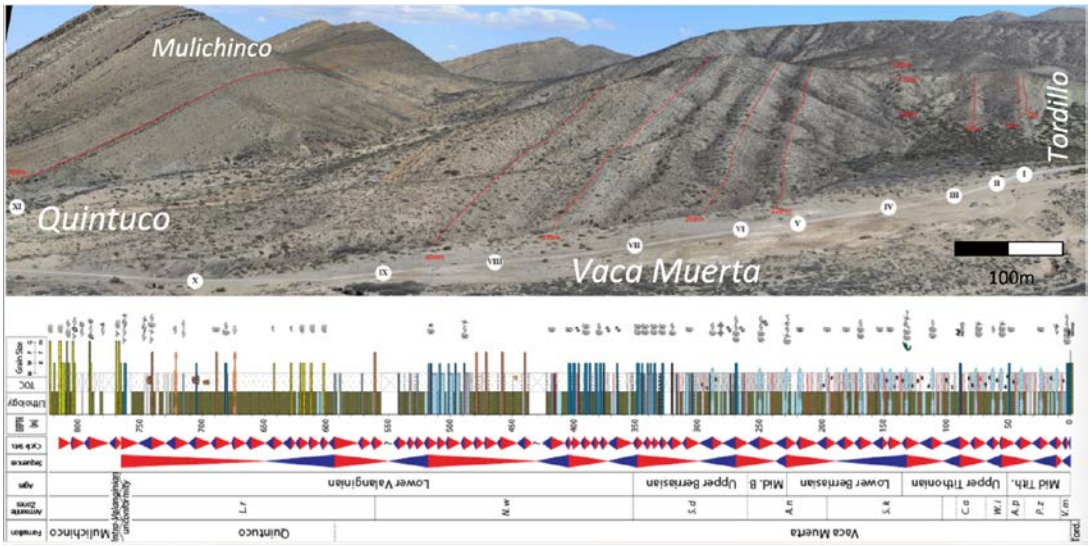

Figure 1. Outcrop view of the Vaca Muerta Formation in the Puerta Curaco area with annotation of the sequence boundaries. In this distal part of the Neuquén Basin the formation is approximately 590 m thick. Splicing together sections produces a reference section that can be correlated and compared to the subsurface.

APPROACH

The approach at the CSL is to conduct detailed studies in the proximal and distal areas of the basin for a comprehensive evaluation of various aspects of that basin. Earlier projects focused on the sedimentologic/stratigraphic evolution of the mixed Vaca Muerta-Quintuco system in the Picún Leufú and Sierra de la Vaca Muerta and its correlation to the subsurface data (Zeller et al., 2015a,b). In the last two years we have focused our research on the distal basin where we have measured many coeval sections in the basinal setting that can serve as a reference section for the bottom set of the Vaca Muerta clinoforms (Fig. 1 and 2). The lithologic, geochemical, and petrophysical properties are measured in each section with high resolution (0.5 – 1 m) that is comparable to log resolution in the subsurface. Thus, this reference section is an outcrop calibrated analog for subsurface cores and logs. In addition, this reference section serves as the basis for individual projects that target fundamental questions regarding the distribution of TOC within the Neuquén Basin.

Figure 2. Location map of the key study areas in the Neuquén Basin, Argentina.

PLANNED PROJECTS FOR 2017

This year's projects address questions surrounding the:

- Lateral Facies Variability and Thickness Changes in a Basinal Setting;
- Depositional and Environmental Controls on Organic Material in the Vaca Muerta Formation;
- High Resolution Elemental, Mineral and Isotopic Assessment of Cycles of the Vaca Muerta Formation, Argentina;
- Temperature of Formation of the Vaca Muerta "Beef" Determined by Clumped Isotopes.

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LATERAL FACIES VARIABILITY AND THICKNESS CHANGES IN A BASINAL SETTING

Ralf J. Weger and the Vaca Muerta Team

OBJECTIVES

- Measure a new section of the Vaca Muerta Formation approximately 5km north of the existing Puerta Curaco reference section to assess the lateral variability in the basin center.
- Refine the Puerta Curaco (PC) reference section measurements and fill-in missing parts.
- Measure a new section in Yesera del Tromen to achieve a better tie to existing published age data.

RATIONALE AND BACKGROUND

In the last two years we have measured several sections in the Puerta Curaco area to produce a reference section without any gaps in coverage. The CSL has assembled a complete section through the Vaca Muerta Formation at Puerta Curaco by splicing together the best-exposed segments of the formation. This composite section provides a formidable framework for a comprehensive assessment of the sedimentological, stratigraphic, petrophysical, and geochemical evolution of the Vaca Muerta Formation in this basinal position.

In each segment the lithologic log is complemented with a gamma ray

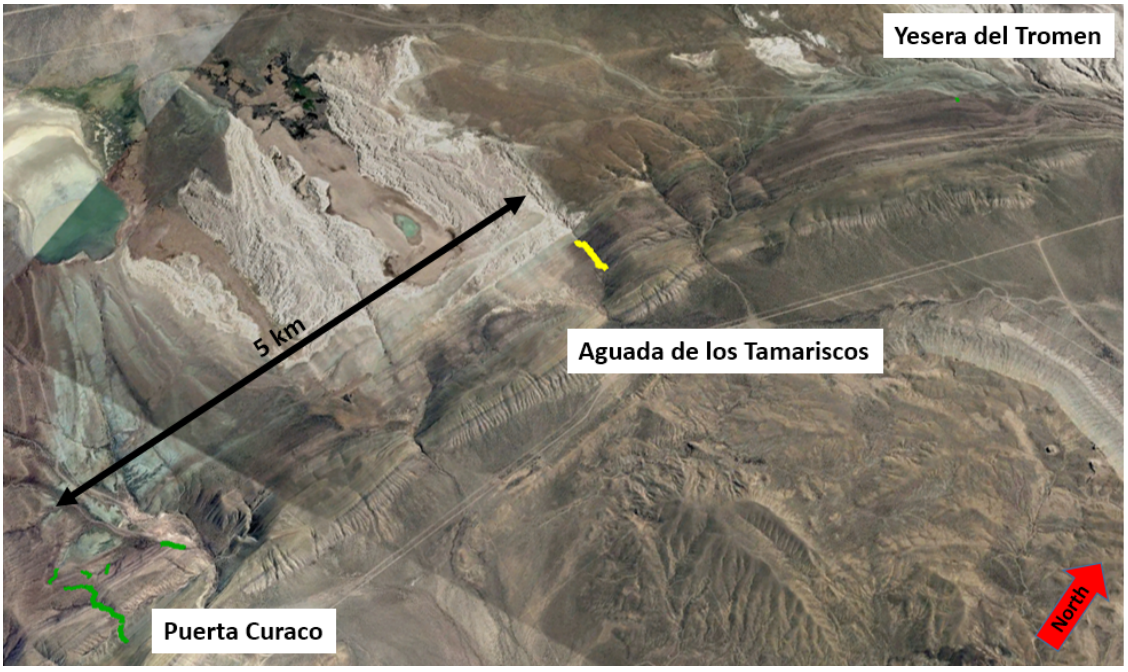

Figure 1. Regional overview and location of sections in Puerta Curaco, Yesera del Tromen, and the new section at Aguada de los Tamariscos.

measurement and samples for chemical analysis at 1 m intervals to build a detailed 1D record of the strata. This sedimentological, geochemical and petrophysical data set can be compared to cores and logs in the subsurface.

The individual segments of the reference section at Puerta Curaco are a couple of hundred meters apart and thus allow for an assessment of the small-scale lateral variability. To capture the variability on a larger scale, we plan to measure a complete section further away from the reference section. This offset section will provide valuable information about the distribution of TOC and strata in this basinal setting.

SCOPE OF WORK AND EXPECTED RESULTS

The new offset section is approximately 5 km north of Puerta Curaco (Fig.1). This new section will provide meter-scale gamma ray measurements and samples for geochemical analyses. In addition, this new section will allow thickness comparisons between the existing PC reference section and another nearby basinal position.

This comparison will allow us to evaluate lateral facies variations, changes in bed and interval thicknesses, and any variability in TOC and carbonate content. Although the distance between the two sections is relatively short, the variation resulting from a 5 km northward movement within this basinal setting may allow us to discriminate a relatively more proximal position from a relatively more basinal setting.

Additional plans for the upcoming field season are to measure a section at Yesera del Tromen that has been dated with ammonites by Aguirre Urreta et al. (2014). This duplication of her section and the exact positioning of her ammonite zones into our section will strengthen the biostratigraphic dating of the reference section that is only a few kilometers away. In addition, it will serve as another anchor point for assessing the lateral variability in the basin.

To improve the splice at the reference section and to be able to better characterize the facies, we will measure short segments with better exposure in the Puerta Curaco area. Another drilling campaign to obtain more 1 m cores from key locations is planned for the spring.

SIGNIFICANCE

The lithology of the various outcrop sections, together with the petrophysical and geochemical properties measured, will provide an array of data points in the basin center that will capture the small and large-scale heterogeneity of the strata.

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DEPOSITIONAL AND ENVIRONMENTAL CONTROLS ON ORGANIC MATERIAL IN THE VACA MUERTA FORMATION

Max Tenaglia, and the Vaca Muerta Team

PROJECT OBJECTIVES

- Produce a comprehensive depositional model identifying the position of organic rich source rocks within the prograding clinoforms in the Neuquén Basin.
- Identify environmental factors conducive to the development of high Total Organic Carbon (TOC) intervals.

PROJECT RATIONALE

The Vaca Muerta Formation gives access to Late Jurassic – Early Cretaceous strata and offers insights into organic-rich intervals within a prograding sedimentary system during a time interval that represents a major carbon sink in the geologic record. The repeated occurrence of TOC-rich intervals determined in outcrop and subsurface at certain sequence stratigraphic levels within the basin center indicates long-term or repeated optimal conditions for the accumulation of organic rich strata. Based on stratigraphic relationships it is our working hypothesis that the distribution of the organic-rich strata is related to the evolution of the prograding clinoforms and thus can be placed into the geometry of the clinoforms (Fig. 1).

While sedimentary rocks high in TOC have been studied for decades, there

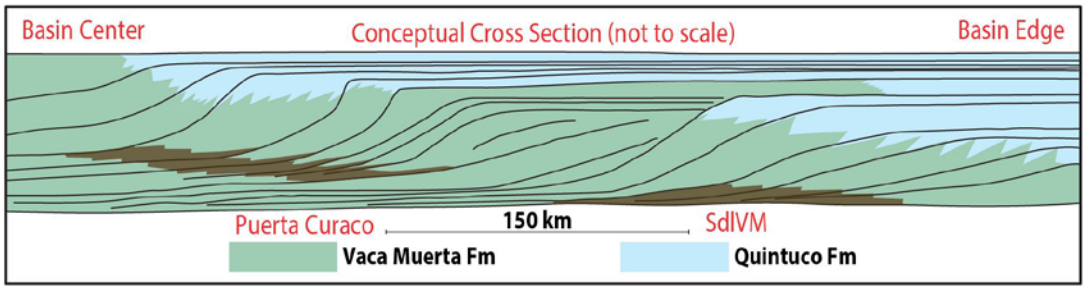

Figure 1. Depositional model of the progradation fill of the Vaca Muerta – Quintuco system. Organic material is concentrated at the extreme toe of slope of the clinoforms.

is still no consensus as to which factors control their deposition. There is, however, agreement in the literature to three main triggers for the presence of organic material in the sedimentary record. These include 1) Production: attributable to high rates of organic productivity, usually stimulated by a high nutrient flow. 2) Preservation; the presence of oxygen-poor bottom waters that limit reactions degrading organic matter. 3) Dilution; decreasing sedimentation rates that would otherwise dilute the concentration of organic matter. It is likely that within portions of the transgressive–regressive cyclicity, each of the three aforementioned primary factors plays a more prominent role.

SCOPE OF WORK

To produce a comprehensive depositional model, our existing TOC dataset will be integrated into the clinoform geometries using a regional seismic transect. To identify environmental factors conducive to high TOC intervals, geochemical proxies are used to identify the controls on organic material. A primary productivity driven model, as suggested by Pedersen and Calvert (1990) would mean that formation of organic-rich rocks is dependent upon elevated productivity - controlled by the availability of nutrients present in the water column. To examine this, samples from identified high TOC intervals will be measured for trace elements (e.g. Ba, P, S) as a proxy of nutrient input and elevated bio-productivity. The organic preservation is achieved by means of a well-stratified water column and anoxia. Such anoxic events manifest themselves in the geologic record in many ways. One, proposed by Gill et al. (2011), is a positive sulfur isotope excursion. These isotopic shifts can be measured in the $\delta^{34}S_{CAS}$ (Carbonate-Associated Sulfur) and $\delta^{34}S_{pyrite}$ and reflect increased organic burial under large scale anoxic and euxinic conditions.

Finally, a sedimentation rate or burial rate driven model has been used to assess dilution as the controlling factor. The "condensed section" model of Creaney and Passey (1993) assumes that as a response to rapid sea-level rise, a condensed section will form associated with the maximum flooding surface. The lack of detrital input will ultimately concentrate the organic matter in the sediment. The "condensed section" model aligns well with the stratigraphically aligned distribution of organic rich intervals observed in the data.

SIGNIFICANCE

This study will document the controls on laterally and vertically heterogeneous organic-rich sediments of the Vaca Muerta Formation. We will identify depositional trends and environmental factors that are conducive to the development of high TOC intervals. While most of this study will be done in outcrop, the inclusion of sub-surface samples from nearby wells will show the strength of using outcrop studies to understand the sub-surface and help improve the exploration efforts in the basin.

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HIGH RESOLUTION ELEMENTAL, MINERAL AND ISOTOPIC ASSESSMENT OF CYCLES OF THE VACA MUERTA FORMATION, ARGENTINA

Laura Rueda, Gregor Eberli, and the Vaca Muerta Team

PROJECT OBJECTIVES

- Conduct an elemental, mineralogical, and isotopic calibration of the depositional cycles of the Vaca Muerta Formation.
- Correlate elemental logs from short cores using X-ray Fluorescence (XRF) to the mineralogy retrieved from X-ray Diffraction (XRD), Near-Infrared Spectroscopy (NIR), and Hyperspectral Core Imaging (HCI).
- Compare the mineralogy in outcrops from XRD, thin sections, NIR, and HCI measurements.

PROJECT RATIONALE

The early Tithonian-Valanginian Vaca Muerta Formation contains cycles of fine-grained calcareous and siliciclastic sediments (Fig. 1), the total organic carbon (TOC) varies through different stratigraphic levels and basinwide. Short-cores (~1m in length) drilled in different stratigraphic levels and different positions of the basin preserve in great detail sedimentary structures and also facilitate the study of the continuous (vertical) lithologi-cal and geochemical variations. Elements and minerals retrieved from short cores and/or outcrops using XRF, XRD, NIR and HCI technologies will provide for the first time a very detailed and continuous mineral calibration of the studied sections in the VM fm.

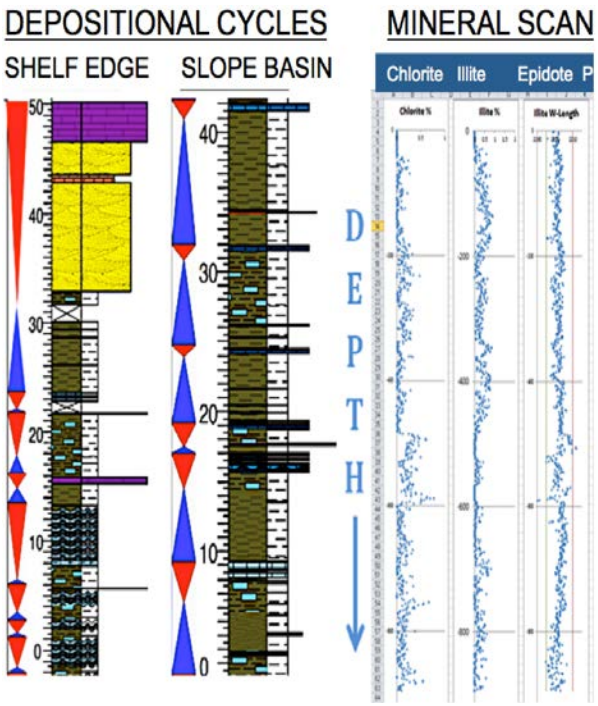

Figure 1. Left: Cycle-sets of the Vaca Muerta Formation in different positions of the basin. Right: Example of minerals calculated in a core using HCI system (image modified from www.corescan.com.au).

SCOPE OF WORK

Measure minerals every 1m using the TerraSpec Halo mineral identifier (NIR system) in different measured sections in the Sierra de la Vaca Muerta (proximal) and Puerta Curaco (distal). Calculate minerals,

mineral alterations, and changes in mineral crystallinity, as well as changes related to geochemical conditions in 80 short cores from outcrop using HCI and NIR systems (Fig. 2). Compare the lithological and the geochemical (NIR, HIC, XRD, XRF, TOC, $\%CaCO_3$, and $\delta^{13}C$ and $\delta^{15}N$ values) results to find associations and variations for a calibration of the logs and cycles. Outcrop analogs and cores from outcrop can aid in understanding the cyclicity and facies distribution and variability in a basin.

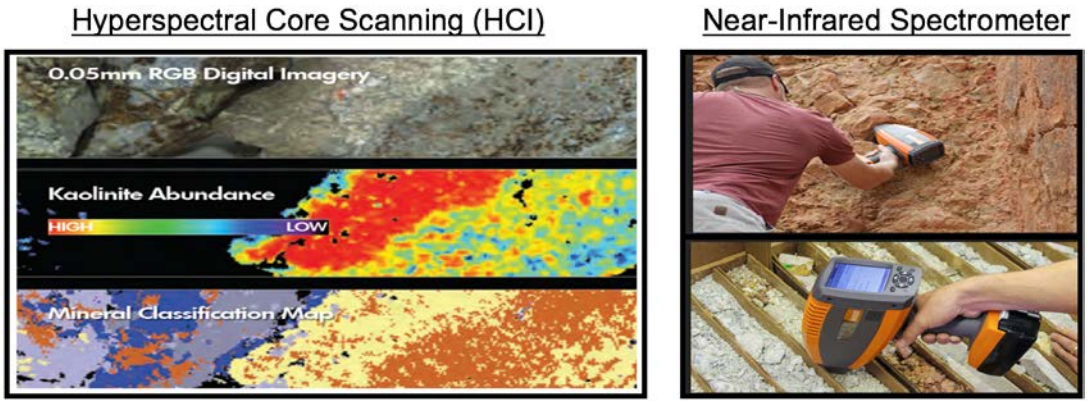

Figure 2. Left: Example of a core scanned for mineral identification using HCI system (image modified from www.corescan.com.au). Right: TerraSpec Halo mineral identifier handheld device being used in the field and in the lab (image modified from www.panalytical.com).

EXPECTED RESULTS AND SIGNIFICANCE

The high-resolution characterization of cores and outcrop from different stratigraphic levels and positions within the Neuquén Basin will be completed using geochemical approaches that include mineral identification using NIR, and hyperspectral core scanning techniques. Additionally, a correlation among minerals, elements (XRF), carbonate content, isotopes and lithofacies will aid in understanding the processes forming and/or disturbing the cycles within the stratigraphic sequences and also will give information about provenance and diagenesis of sediments.

A high-resolution geochemical and lithological study of the cycles in outcrops and cores from proximal and distal positions within the basin is required in order to quantify basinwide variations and to correlate them to log data. The lithological and geochemical signals placed into the already established stratigraphic framework will provide the basis to predict cycles in sectors of the basin with wells but without sediment cores.

TEMPERATURE OF FORMATION OF THE VACA MUERTA "BEEF" DETERMINED BY CLUMPED ISOTOPES

Ralf J. Weger, Donald F. McNeill, Sean Murray, Peter K. Swart,
Gregor P. Eberli, and the Vaca Muerta Team

PROJECT OBJECTIVE

- Determine the temperature and the lateral variation in temperature and fluid composition of the beef calcite using stable $\delta^{13}C$ and $\delta^{18}O$ values and the clumped isotope paleo-thermometer.

PROJECT RATIONALE

Many fissile mudstones around the world that are unconventional resource plays show abundant bedding-parallel calcite veins, often within the organic-rich, sometimes clay-rich matrix. Such bedding-parallel expansion seams were described by Sorby (1860) who originally coined the term "beef-in-shales." Other occurrences have been described as horizontal fractures or fibrous veins. In the Vaca Muerta, abundant beef calcite within organic-rich mudstone can be observed across all of our studied sections. In the sections from the Sierra de la Vaca Muerta, beef is generally limited to thin (<1-2 cm) features, restricted in lateral extent. In the more basinal facies in sections around Puerta Curaco (PC), beef occurrences are more dominant, both with respect to thickness and abundance, as well as with respect to lateral continuity. In addition, some beef occurrences are of such lateral persistence, that they clearly represent a feature able to provide in-field well-to-well correlation. Several publications associate bed-parallel expansion seams with high temperature and localized overpressure conditions that existed at the time of hydrocarbon generation and correlate to its thermal maturity (Cobbold et al., 2013; Rodrigues et al., 2009).

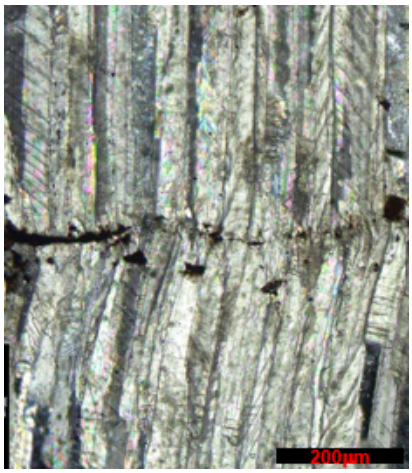

Figure 1. Photomicrograph of a PC Beef sample showing crystal termination along the central seam of the calcite crystals.

SCOPE OF WORK

As a first step, we used petrographic analysis as well as $\delta^{13}C$ and $\delta^{18}O$ values of Vaca Muerta beef in order to generate a vertical transect across a 6 cm thick sample to establish its internal growth symmetry (Fig. 1). Both carbon and oxygen isotopic values of Vaca Muerta beef were compared to a variety of other materials from the Puerta Curaco section of Vaca Muerta. The $\delta^{18}O$ values of the PC beef ranged between -9 and -11‰, the $\delta^{13}C$ values

varied between 0 and +2‰. In contrast, $\delta^{18}O$ values of the sampled concretion matrix material ranged between +1 and -3‰ with $\delta^{13}C$ values ranging from +5 to +10‰. All other sample material; fracture fill calcite from two concretions and the mudstones surrounding the sampled beef show $\delta^{18}O$ values substantially more negative (-7 to -9‰) than the sampled concretion matrix material. Both the $\delta^{13}C$ and $\delta^{18}O$ values of the background mudstone surrounding the beef sample are similar to those of the beef itself and the concretion fracture fill calcite. Assuming similar isotopic properties of the formation fluids, the more negative values of $\delta^{18}O$ would suggest significantly higher formation temperatures for the beef and the fracture fill calcite when compared to the concretion matrix material. Clumped isotope analysis suggest formation temperatures of Vaca Muerta beef to be approximately 110°C with formation fluid $\delta^{18}O$ values of 6 to 6.5‰, whereas the mudstones 50 cm above and below the beef show temperatures of approximately 100°C but formation fluid $\delta^{18}O$ values ranging from 6 to over 8‰.

In future work we intend to extend the clumped and C and O isotopic analyses over the entire lateral extent of the beef as well as examining other beef layers in the strata, and also the associated nodules and carbonate occurrences.

SIGNIFICANCE

Beef veins form symmetrically from the edge to the center, showing crystal terminations, oil or bitumen residue, and occasionally a central open void (Fig. 1). This pattern of formation suggests that overpressure may have produced the original opening and that hot fluids attempting to escape are responsible for the formation of beef. These results are consistent with the hypothesis put forward by Rodriques et al. (2009) that overpressure and horizontal compression was responsible for the Vaca Muerta beefs.

Clumped isotope measurements of Vaca Muerta beef indicate that the calcite in the beef was formed at a temperature of approximately 110°C in concert with the burial depth of the Vaca Muerta Formation. If these calcite veins indeed represent the burial depth, the clumped isotope method would be an excellent tool to track the burial history of sedimentary basins and to assess at which depth burial diagenesis is most important.

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ACOUSTIC AND ELECTRICAL PROPERTY CHARACTERIZATION OF THE VACA MUERTA FORMATION

Mustafa K. Yüksek Ralf J. Weger, Gregor P. Eberli, and the Vaca Muerta Team

PROJECT OBJECTIVES

- Produce a comprehensive petrophysical data set (porosity, acoustic velocity, resistivity, permeability, and pore structure) of the facies in the Vaca Muerta Formation.
- Define the control of mineralogy and clay content on the petrophysical properties and, in particular, the acoustic anisotropy.
- Examine the relationship between clay content, acoustic velocity, and resistivity to find differences between ductile and brittle behavior of the mudstones of the Vaca Muerta Formation.

PROJECT RATIONALE

Plug samples from 1m short cores through the various facies of the Vaca Muerta Formation enable us to petrophysically characterize each facies and produce a wide-ranging catalogue that relates petrophysical properties such as porosity, acoustic velocity, resistivity, and permeability to the rock composition and pore structure. Special emphasis will be given to the acoustic anisotropy of these rocks. The amount of clay also influences the anisotropy of the fissile mudstones in the Vaca Muerta Formation. The Vertical Transverse Isotropy (VTI) of these rocks is mostly used for interpretation and processing of seismic data. Yet, anisotropy needs to be taken into account in a variety of processing steps, such as normal move-out (NMO) and dip move-out (DMO) corrections, migration, and amplitude variation with offset (AVO) analysis, and depth conversion.

BACKGROUND

The compressional wave velocity is a function of porosity, the velocity of matrix (V_m), and the velocity of pore fluid (V_f) as described by the time-average equation (1) of Wyllie et al. (1956).

$$\frac{\mathbf{1}}{\boldsymbol{Vp}} = \frac{(\mathbf{1}-\emptyset)}{\boldsymbol{Vm}} - \frac{\boldsymbol{O}}{\boldsymbol{Vf}} \quad (1)$$

or by Raymer et al. (1980) whose equation (2) is adjusted for well log data.

$$\boldsymbol{Vp} = (\mathbf{1}-\emptyset)^{\mathbf{2}}\boldsymbol{Vm} + \emptyset\boldsymbol{Vf} \quad (2)$$

The acoustic velocity of the matrix is directly related to its mineralogical composition, which in mudstones is often tied to the amount of clay. Clay content influences anisotropy and the ratio between compressional and shear wave velocity (V_p/V_s). The latter is an important variable for detection of rock properties. The influence of clay content (C) in the matrix on the V_p/V_s ratio is described in the empirical equation (3) from Han et al., (1986).

$$\mathbf{V_p/V_s = 1.55 + 0.56\emptyset + 0.43C} \quad (3)$$

SCOPE OF WORK

Seventy-nine 1 m short cores have been drilled in key locations throughout the over 1200 m of measured sections of the Vaca Muerta Formation. These cores have previously been analyzed with regards to mineral composition and gamma ray. This study complements these datasets with petrophysical properties (porosity, acoustic velocity, resistivity, permeability, and pore structure) focusing on the anisotropy and provides VTI constants $\varepsilon, \delta,$ and γ within the Vaca Muerta Formation. In addition, the variability in resistivity between the carbonate-rich intervals and pure siliciclastic rocks will be investigated.

The mineralogical data will be correlated with the petrophysical properties and used to calculate the V_p/V_s ratio in order to assess the causes of the anisotropy. Together this data set will aid in the seismic processing and, thus, reduce the interpretation risk for unconventional exploration.

SIGNIFICANCE

The planned mineral identification, determination of the distribution and quantity of clay type, and the assessment of their effects on petrophysical properties of the Vaca Muerta Formation is an innovative test of the Han et al. (1986) equation and the influence on anisotropy. Furthermore, the study will produce a comprehensive data set of mineralogical and petrophysical properties that is not yet available for organic-rich fissile mudstones targeted in unconventional plays.

Better knowledge of well documented acoustic and electrical properties of some of the facies in the Vaca Muerta Formation will improve well log interpretation. Furthermore, successful extraction of core plugs at three different angles, and elucidation of the resulting anisotropy parameters, will aid and improve seismic processing and result in better imaging. Improving 3D seismic images will add value through optimizing drilling operations and hydraulic fracturing efforts.

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GEOMICROBIOLOGY OF HOLOCENE FRESHWATER MICROBIAL MUD IN THE FLORIDA EVERGLADES

Chelsea L. Pederson, James S. Klaus, Donald F. McNeill, and Peter K. Swart

PROJECT OBJECTIVES

- Link depositional and diagenetic signatures to microbial communities and metabolic processes (sulfate reduction, denitrification, etc.) using high throughput DNA sequencing of *in-situ* sediment samples.
- Characterize the textural evolution of modern and recently buried freshwater carbonate mud in south Florida.
- Evaluate the primary depositional signature and early diagenetic changes using geochemical analyses of sediments, organics, and pore waters.

PROJECT RATIONALE

As microbial processes can affect both the precipitation and dissolution of carbonate grains, their importance in diverse depositional settings is increasingly recognized. The Florida Everglades is a site of fine-grained carbonate production via microbial processes within a palustrine setting. However, while microbial communities have been shown to play a role in carbonate precipitation, their effect on early diagenetic alteration of the resultant calcitic mud is poorly known and largely undocumented. The objective of this project is to better characterize the secondary processes occurring in various early burial environments in order to evaluate the preservation potential of original geochemical and textural signatures in palustrine carbonates.

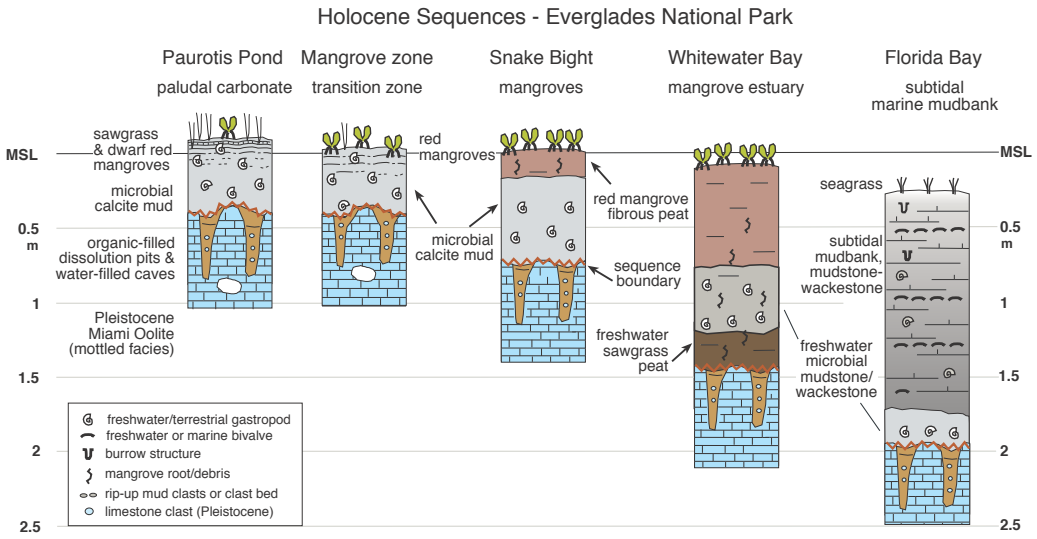

Figure 1. Schematic transect of variations in early burial of Holocene freshwater muds; freshwater (Paurotis Pond) to marine (Florida Bay) transition.

In south Florida, Holocene freshwater microbial mud is found overlying Pleistocene limestone bedrock from inland sites (currently forming), seaward to Florida Bay (Fig. 1) where it is buried by marine sediment. Progressively buried during the marine transgression, the carbonate mud is now subjected to various pore fluid regimes: freshwater, brackish, and full marine along the transect. The inland sites host active microbial carbonate formation. The brackish zone has formed as microbial deposits were buried during the Holocene transgression. Overlying brackish deposits include organic-rich sediments and surface seasonal salinity changes. At Florida Bay, freshwater muds were identified beneath both the coastal levee and mangrove-capped islands in the Bay. Analyzing the muds and pore waters in these various environments will help assess the impact of microbial metabolisms and changes in pore water chemistry on carbonate crystals during the early burial process. These diagenetic environments can be assessed for changes to organic matter composition, carbonate texture, and geochemical signatures.

SCOPE OF WORK

Textures— In order to best identify changes in textures during the burial process, we will analyze sediment from six different burial environments including the modern freshwater zone, the brackish transition zone, and the fully marine environment. Grain-size analyses along with scanning electron microscopy will be used to assess textural changes to the carbonate mud.

Geochemistry— Analyses will be run on sediments, organics, as well as interstitial pore water in order to best characterize the primary and diagenetic signals of the Holocene mud deposits. Analyses will include mineralogy, inorganic $\delta^{13}C$ and $\delta^{18}O$, total organic carbon (TOC), organic $\delta^{13}C$ and $\delta^{15}N$, trace element composition using standard ICP-OES methods, alkalinity, and dissolved inorganic carbon (DIC).

Geobiology— We will analyze the microbial communities and their effect on carbonate diagenesis across varying surface sediments and in core profiles of the Holocene deposits. Microbial communities will be documented across the laterally heterogeneous environments. Genomic DNA will be extracted and sequenced using Metagenomic Illumina techniques to characterize total DNA in each sample, providing information on both the community structure, as well as the microbial metabolisms (i.e. photosynthesis, sulfate reduction, denitrification) occurring within the sediment.

SIGNIFICANCE

The integrative nature of this project will allow linkage of textural and geochemical signatures to depositional and diagenetic processes. This will change our understanding of how freshwater microbial muds are deposited and altered over time, and with respect to burial environment. This will help evaluate the preservation potential of primary depositional markers, and allow for more accurate interpretation of the depositional setting in which freshwater palustrine carbonates have formed.

USING CLUMPED ISOTOPES TO CONSTRAIN DIAGENETIC TEMPERATURES IN OCEANIC AND PERIPLATFORM CARBONATES

Philip T. Staudigel and Peter K. Swart

PROJECT OBJECTIVES

- Use of the clumped isotope proxy as a method to constrain rates of diagenesis in oceanic sediments.
- Calibrate existing diagenetic models based on geochemical and physical data.

PROJECT RATIONALE

Estimating recrystallization can be carried out by (i) physical examination of the sediments, (ii) measuring the concentration of trace elements in the interstitial pore waters and in the sediments themselves (Swart and Guzikowski, 1988), (iii) measuring the $\delta^{18}O$ values of the sediments and pore waters (Lawrence, 1989), (iv) measuring the $\delta^{44}Ca$ and $\delta^{26}Mg$ of the sediments and porewaters (Higgins et al., in Preparation). Results from the geochemical analyses need to be modeled while making numerous assumptions about the depositional history. In this project we propose to compare rates of diagenesis calculated using these methods with those estimated using the clumped isotope technique.

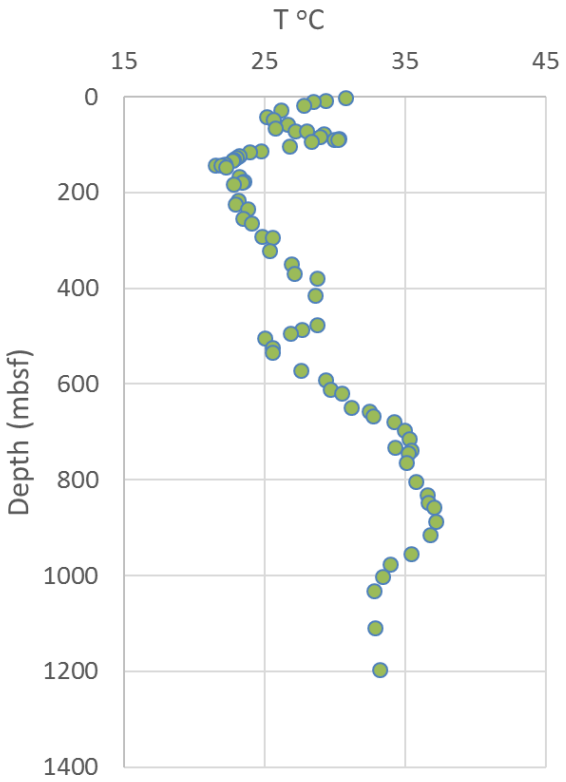

Figure 1: The clumped isotopic derived temperature from Site 1003. Points represent a five sample smooth value.

SCOPE OF WORK

The work outlined here proposes to analyze materials collected from several Ocean Drilling Program (ODP) and International Ocean Discovery Program (IODP) locations.

Bahamas: Seven cores were drilled during Leg 166 on the margin of Great Bahama Bank (GBB). Five of these were taken on an extension of the seismic line (Eberli, 2000) which

intersected cores (Clino and Unda) drilled on the surface of GBB. The deepest of these cores (1003) penetrated earliest Miocene at a depth of 1300 mbsf. All of the cores show extensive recrystallization. Geothermal profiles, pore water and carbonate $\delta^{18}O$ values exist for all sites. Preliminary clumped isotopic temperatures are shown in Figure 1 and indicate the recrystallization/neomorphism of shallow water derived sediments in colder waters in the upper 200 mbsf, followed by increasing equilibrium with the geothermal gradient further down the core.

Maldives: We have collected materials (sediments and porewaters) from cores retrieved during Expedition 359 in the Maldives. This expedition drilled sites adjacent to carbonate platforms similar to the Bahamas. These locations appear to be heavily diagenetically altered, but in contrast to the Bahamas there is little evidence of active diagenesis in the pore fluids and there is a very weak geothermal gradient.

SIGNIFICANCE

The work outlined here aims to measure the Δ_{47} in a variety of different types of modern carbonate sediments and then trace this signature through recrystallization in the marine burial realm. This work will be an essential prerequisite before utilizing the Δ_{47} in ancient carbonate sediments to indicate the temperature of sediment formation and/or recrystallization as well as the $\delta^{18}O$ of the diagenetic fluid. Although there have been a number of calibrations which have dealt with individual biogenic components, there have been no studies attempting to explain the Δ_{47} of bulk carbonate sediments. This is in spite of the fact that an increasing number of studies utilizing clumped isotopes as diagenetic indicators have been applied to samples where the original rocks were not composed of a single component, but rather mixtures of many biogenic allochems.

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EFFECTS OF SEAWATER Mg^{2+} AND Ca^{2+} CONCENTRATIONS ON SR, MG, AND S ELEMENTAL PARTITIONING IN SCLERACTINIAN CORALS

Sharmila J. Giri and Peter K. Swart

PROJECT OBJECTIVES

- To further our knowledge of the partitioning of trace and minor (B, S, Sr, Mg, and Ba) elements into coral carbonates in relation to the Mg^{2+}/Ca^{2+} ratio of seawater.
- To investigate the influence that the Mg^{2+}/Ca^{2+} ratio of seawater has upon growth rate.

PROJECT RATIONALE

Approximately 30 years ago a theory was introduced which suggested that the oceans had undergone transitions between periods when aragonite was the primary calcium carbonate produced by shallow water calcareous organisms and precipitated inorganically from the oceans to times when it was low Mg-calcite (LMC) (Sandberg, 1983). The favored explanation for the alteration between so-called aragonite and calcite seas is that the Mg/Ca ratio of ocean water (Mg/Ca_{sw}) has varied through time (Hardie, 2003), although other work has suggested that the sulfate concentration of the ocean may be important (Bots et al., 2011). One of the supporting lines of evidence of the change in ocean chemistry has been obtained from the elemental analysis of scleractinian coral skeletons which have remained unaltered (Gothmann et al., 2015). Hence, it would be important to know if the distribution coefficients for various elements remain independent of the concentration of elements such as Mg^{2+} and Ca^{2+}.

SCOPE OF WORK

In order to test the assumption that distribution coefficient (D) values are independent of the changes in the major element chemistry of ocean water, we have grown corals in seawater where the Mg^{2+} and Ca^{2+} concentrations have been altered. Three phases of experiments have been completed. These include experiments in which the concentrations of Ca, Mg, and S were increased and decreased. The concentrations were changed to match relevant seawater Mg^{2+}/Ca^{2+} ratios similar to those of the Triassic, Cretaceous, Eocene, and Miocene. Throughout the experiment the calcification rates of the corals were measured and the seawater chemistry monitored. At the termination of the experiment the coral skeletons were analyzed for a range of minor and trace elements. An example of preliminary data is shown in Figure 1 which reveals that the distribution coefficient for Sr (D_{Sr}) is dependent upon the Ca^{2+} concentration of seawater. A final set of experiments will be carried out in 2017.

SIGNIFICANCE

This work has implications for understanding the potential of coral carbonates to act as paleoenvironmental proxies of changes in seawater chemistry. In particular, the data shown in Figure 1 reveal that the application of a single D_{Sr} value throughout periods during which seawater Ca^{2+} concentration change may not be valid. These findings may also be applicable to non-biogenically produced carbonates. The finding of an increasing D_{Sr} also provides key insights into the biomineralization processes in scleractinian corals.

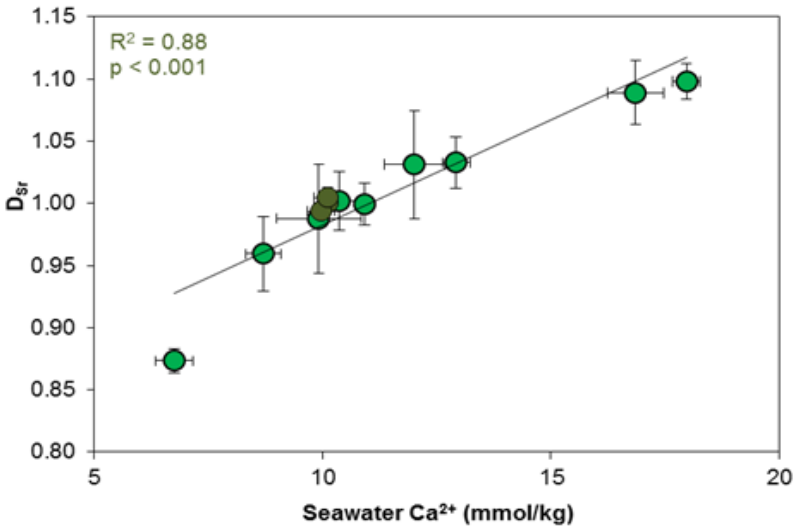

Figure 1: Changes in the D_{Sr} for corals as a function of the Ca^{2+} concentration in the seawater. The grey symbols show data obtained during a second experiment. The results were obtained by both lowering and increasing Ca^{2+} concentrations. These results imply that the application of a single D_{Sr} value throughout time is not valid.

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BORON AND SULFUR ISOTOPES: ORIGINAL SIGNALS OR DIAGENETIC INDICATORS?

Sean Murray, Amanda M. Oehlert, Ali Pourmand, and Peter K. Swart

PROJECT OBJECTIVES

- To understand changes in the B and S isotopic composition of carbonates subjected to well-constrained diagenetic conditions.
- Apply B and S isotopic systematics to ancient sediments for the purposes of constraining the paleoenvironment and paragenesis.

PROJECT RATIONALE

While sulfur ($\delta^{34}S$) and boron isotopes ($\delta^{11}B$) have been used to interpret changes in oceanic conditions during the Neogene, they have also been used in much older materials extending back into the Proterozoic. For example the S isotopic composition ($\delta^{34}S$) of carbonate associated sulfate has been used to interpret changes in the burial of organic material (Lyons et al., 2005) and weathering from continental sources, while B isotopes ($\delta^{11}B$) have been used as a paleo pH proxy (Kasemann et al., 2010) during snowball earth and other climate events such as those identified at the Permo-Triassic boundary (Clarkson et al., 2015). This study is investigating the diagenetic influences upon both of these proxies by examining their behavior in sediments, which have experienced well constrained diagenetic conditions.

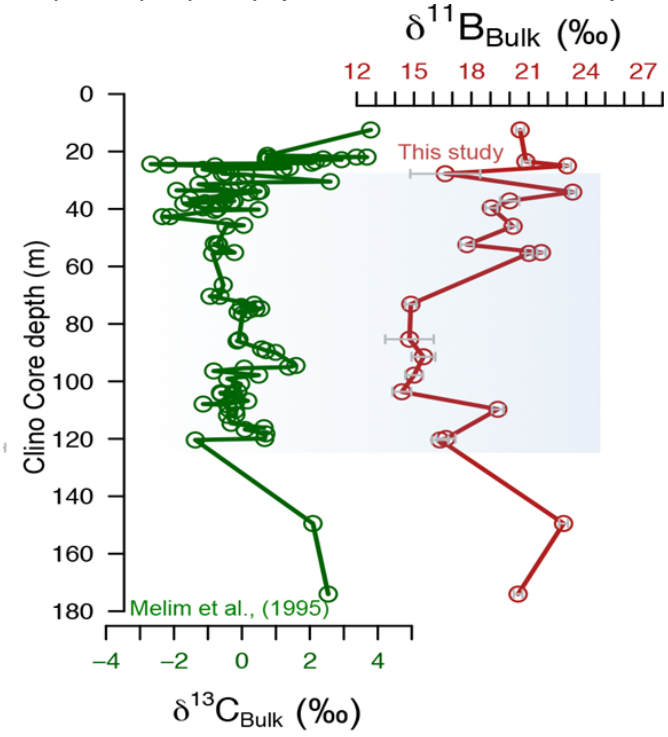

Figure 1: Changes in the $\delta^{11}B$ and co-occurring variations in the $\delta^{13}C$ in the Clino core taken on Great Bahama Bank. The large change in $\delta^{11}B$ could be interpreted as reflecting changes in oceanic pH, but in this case is associated with freshwater diagenesis. Data from Stewart et al. (2015) and Melim et al. (2001).

SCOPE OF WORK

The work outlined here proposes to make measurement on materials collected from environments with established diagenetic histories. These materials will include cores taken in the shallow sub-surface of the Bahamas (Clino and Unda) as well as cores drilled during the Ocean Drilling Program and the

International Ocean Discovery Program. From the Clino cores samples will be taken through the zones affected by vadose, freshwater, mixing zone and marine diagenesis. Preliminary results from core Clino shows changes in the $\delta^{11}B$ values associated with freshwater diagenesis (Fig. 1). We are interpreting this change as reflecting cementation associated with the water table. Sampling will be extended to the base of the Clino core and sulfur isotopic measurements will be made on the same samples. Samples from marine cores will be taken across a non-depositional surface, zones affected by bacterial sulfate reduction, zones influenced by advective fluid flow, and zones characterized by diffusive process.

SIGNIFICANCE

Knowledge of the past pH of the oceans is an important control on the conditions under which past carbonates were formed. Similarly, the S isotopic composition of the oceans places important constraints upon the burial and the oxidation of organic material. The important question addressed by this research is whether these geochemical proxies can survive diagenetic processes and, if not, can the information contained in these records be used to understand the diagenesis of carbonates and help constrain paragenesis.

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CLUMPED ISOTOPES: THE FUTURE

Peter K. Swart

PROJECT OBJECTIVES

- Acquisition of the next generation of clumped isotope instrumentation.
- Automation of procedure.
- Understanding of artifacts associated with the procedure.

PROJECT RATIONALE

The clumped isotope method for the direct determination of temperatures in carbonates has only been around for 10 years, yet its influence on the field has been profound! Since the pioneering work of Ghosh et al. (2006) the number of papers per year has increased from ~3 in 2006 to over 50 in 2016 (Fig. 1) and of these papers the predominant application is in the field of carbonate diagenesis. The stable isotope laboratory, which is part of the CSL, has just started to publish its first papers (Murray, 2016; Murray et al., 2016; Swart et al., 2016; Vahrenkamp et al., 2014) on clumped isotopes and in 2016 hosted the 5th international clumped isotope workshop. However, despite the success of the clumped isotope method the principal instrument used for clumped isotopic analyses, the Thermo 253, has an important design flaw, mainly the occurrence of a negative base line at masses 47-49 which seriously impacts the calculation of the Δ_{47} (He et al., 2012). The result of the negative baseline is that there is a positive correlation between δ47 and Δ_{47}, the slope of which changes with time and varies significantly between different laboratories. Our laboratory has one of the steeper slopes. While it is possible to correct for the base line by measuring the base line adjacent to the mass 47 peak and then adding this to the mass 47 peak, this solution is not ideal and necessitates a significant number of extra analyses of standard gases. An example of the sloping relationship between δ47 and Δ_{47} and the corrected relationship is shown in Figure 2. The solution to the dilemma is a new generation of instruments such as the Thermo 253 plus and the Nu Perspective, which do not have the negative base line. Instruments such as the Thermo 253 plus also have the added capability of having amplifiers which are an order of magnitude more sensitive allowing smaller samples to be analyzed.

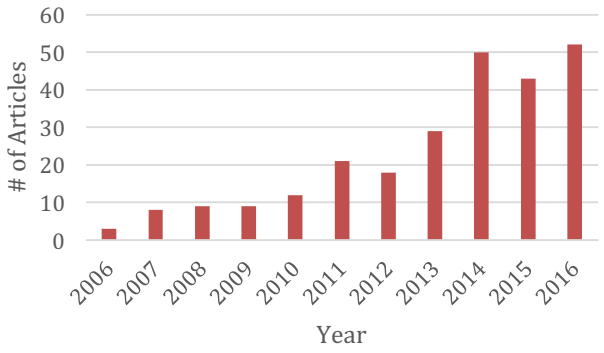

Figure 1: Number of citations in the ISI citation index with the keyword 'clumped isotope' since the first paper was published in 2006 on clumped isotopes in carbonates.

SCOPE OF WORK

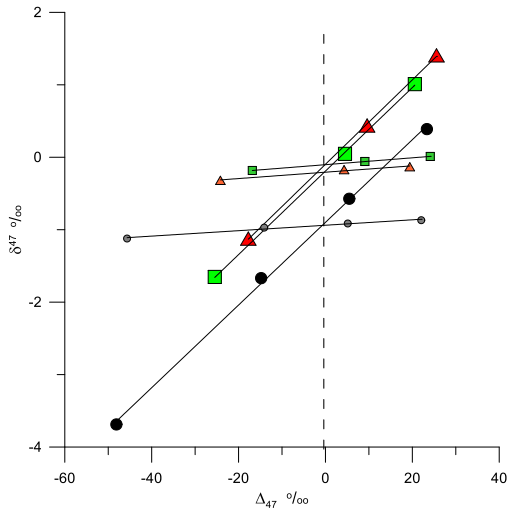

Figure 2: Comparison of the Δ_{47} and δ^{47} relationships with (shallow slope lines) and without (steep slope lines) the correction for the negative base line. The black dots represent the 1000°C heated gases, the green the 50°C equilibrated gases and the red the 25°C equilibrated gases. The correction made by measuring the background makes the relationship approximately horizontal.

We propose to acquire the funding for the purchase a new instrument to be housed at the University of Miami.

The procedure currently employed in our laboratory is completely manual. We can measure about four samples a day, one of which is a standard. With the acquisition of the new instrument we propose to transfer one instrument to an automated system.

There is still a significant uncertainty regarding artifacts associated with the extraction procedures. Notably (a) the isotopic exchange between the CO_2 and the phosphoric acid, (b) the fractionation factors as a function of temperature for different carbonate minerals, and (c) the influence of the extraction method itself upon the $\delta^{18}O$, $\delta^{13}C$, and Δ_{47}.

SIGNIFICANCE

The measurement of Δ_{47} has emerged as an essential tool in any study of carbonate diagenesis and the University of Miami is one of less than 25 laboratories worldwide capable of making such measurements. The acquisition of this equipment will be vital for the future of the stable isotope facility and the excellence of the CSL.

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