CSL
Center for Carbonate Research *and Education*

Prospectus
2021



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 is to conduct fundamental research in carbonates for improved reservoir prediction and characterization.

Our research program is designed to cover four major areas of carbonate geology using and exploring new techniques in a variety of emerging topics. In addition to the fundamental knowledge gained from these studies we aim to inform our industrial associates regarding the newest research techniques that potentially can be incorporated into the workflow of projects or help to solve longstanding problems in exploration and production.

The projects integrate geology, geophysics, geo-microbiology, and geochemistry and combine observational, laboratory, and theoretical research, covering four areas:

- Modern and Ancient Carbonate Systems
- Petrophysics and Near-Surface Geophysics
- Unconventional Reservoirs
- Geochemistry and Geo-Microbiology of Carbonates

Performing research within these four general research disciplines allows us to address fundamental questions in carbonate research in a comprehensive way. As a consequence, some of the research projects are interdisciplinary while others are designed to advance knowledge in one specific area. The various projects 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.

We offer field seminars and in-house short courses.

A Certificate Program in "Applied Carbonate Geology" gives geoscientists the opportunity 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. Also on request, we offer **webinars** of various aspects of our research to our Industrial Associates.

PERSONNEL

PRINCIPAL INVESTIGATORS

Gregor P. Eberli	Professor, Seismic Stratigraphy
Sam Purkis	Professor, Sedimentology
Peter K. Swart	Professor, Geochemistry
James S. Klaus	Associate Professor, Paleontology
Amanda M. Oehlert	Assistant Professor, Geochemistry
Donald F. McNeill	Scientist, Sedimentology, Stratigraphy
Mara R. Diaz	Scientist, Geobiology
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Greta J. Mackenzie	Associate Scientist, Petrography
Mark Grasmueck	Adjunct Professor, Subsurface Imaging
Paul (Mitch) Harris	Adjunct Professor, Applied Sedimentology

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G. Michael Grammer	Oklahoma State University
Langhorne Bullit "Taury" Smith	Smith Stratigraphics, New Orleans
Leticia Rodriguez Blanco	Consultant, Buenos Aires, Argentina
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2021 RESEARCH FOCUS

The pandemic of 2020 disrupted our planned fieldwork in the Maiella (Italy) platform and the research expedition to the Mozambique Channel. However, OceanX 'Deep Blue' research cruise was completed in the Fall of 2020 in the northern Red Sea. The goal of the expedition was to capture the diversity in styles of **deposition in an active rift basin**. A wealth of geophysical data was collected and ground-truthed by >400 hours of ROV and submersible dives. Sediment and water samples complement this comprehensive dataset. This project and the study of **carbonate contourite systems** are the focus of the **deep-water carbonate research**. Three projects are planned for carbonate contourite systems. First, we continue to expand our database on the dimensions, composition, and petrophysical properties of carbonate drifts in different tectonic settings and times. Seismic and core data from the Ocean Drilling Program will be used to examine the formative role of ocean currents on the flanks of carbonate platforms. Fieldwork on the Maiella drift delta will investigate the processes forming coarse-grained current deposits. The overall goal of these studies is to complement the models of carbonate deep-water deposition that has concentrated on gravity flows. These sedimentologic and petrophysical models are expected to help de-risk deep-water plays.

The **shallow-water carbonate** projects examine the small- and large-scale evolution of carbonate systems. One project uses seismic and well data to unravel the tectonic and stratigraphic evolution of the Yucatan Platform, influenced by regional Caribbean tectonics, sea-level controlled infill of a platform interior trough, as well as the Yucatan Current, at least in the Neogene portion. The analysis of heterogeneity on a reservoir scale is the subject of a project that examines the evolution of a modern ooid sand island at Joulter Cays (Bahamas). The influence of diagenesis on petrophysical properties is investigated in two projects. One evaluates the influence of early, pre-burial meteoric diagenesis on the flow properties of ooid grainstones with whole-core constant-head hydraulic conductivity measurements on cores of cross-stratified Miami Oolite. The other project compares the influence of biologically-mediated versus inorganic-precipitated cements on acoustic velocity and rock strength of ooid grainstones.

In recent years, two new methods (accommodation succession and stratigraphic surface methods) have been proposed for conducting sequence stratigraphy in siliciclastic systems. Applying these methods in **carbonate sequence stratigraphy** has been a challenge, because some of the underlying assumptions in these methods are hard to reconcile with processes in carbonates. A large initiative within the carbonate community is underway to evaluate these new methods in carbonates. Two projects at the CSL are part of this effort. One interrogates seismic and outcrop data to assess where surfaces relevant for sequence stratigraphy fall in a base-level cycle in carbonates. We compare these results to the surfaces proposed in siliciclastic sequence-stratigraphic models. A second project examines the geochemical expression of sequence boundaries.

The **geochemistry** projects focus on two main themes. One compares various isotopic patterns in the Pacific and Atlantic to assess if diagenetic events, in particular meteoric diagenetic overprint from sea-level falls, produce global shifts in $\delta^{13}C$ and $\delta^{18}O$ values that have traditionally been explained by changes in ocean chemistry. The method of rolling window regression (RWR) will help to identify types of diagenetic processes and the presence of global patterns in $\delta^{13}C$ and $\delta^{18}O$ values. In addition, boron, sulfur, and clumped isotopes will be used to discriminate between marine and meteoric diagenesis. The second main focus in geochemistry is the refinement of the **clumped isotope method** (Δ_{47}). The clumped isotope value can be used as a temperature proxy, but some carbonate secreting organisms precipitate calcium carbonate out of equilibrium, making an accurate temperature estimate uncertain. Incorporating the clumped isotope with mass 48 can help to eliminate any uncertainty. The stable isotope laboratory within the CSL has established the calibration of this clumped isotope for carbonates precipitated at nine temperatures (5 to 73^{o}C) and reacted at 90^{o}C in a common acid bath. This calibration allows us to investigate the Δ_{48} values in a number of systems which exhibit non-equilibrium precipitation behavior as regards their Δ_{47} values.

For many years we have explored the control pore structures have on the petrophysical properties of carbonates. Our large database of velocity and resistivity measurements gives us the opportunity to assess how accurately one can discriminate connected interparticle- from separated-moldic porosity using these two petrophysical properties. This year, however, our research in **petrophysics** includes an examination of the **influence of diagenesis** on petrophysical properties. The reason for this inclusion is that diagenetic processes have a strong control on both the pore structure, but also on frame stiffness. In two projects we evaluate the different response of early microbial-induced marine cements versus meteoric cements on velocity and permeability, respectively. The effects of multiple diagenetic events on velocity and resistivity on shallow and deep-water carbonates is assessed in a project using the cores and logs along the Bahamas Transect.

In the last ten years, we have conducted multi-disciplinary research in the **unconventional reservoirs in the Neuquén Basin**, focusing on the Vaca Muerta-Quintuco system. We have assembled a comprehensive database and plan to write a field guidebook that summarizes our outcrop results. In conjunction with this effort, we prepare a virtual fieldtrip that will give scientists the opportunity to visit the outcrops of the **Vaca Muerta Formation** in an "Interactive Multiuser Virtual Reality" environment. With the outcrop work in the Vaca Muerta basically completed, we start to compare and correlate our results to the subsurface. For example, we evaluate the similarities and differences of compositional variations in sequences and cycles in outcrop and in the subsurface with a semi-quantitative analysis of thin section of our measured sections. We also seek to get additional subsurface data for such comparisons.

We embark in a new direction in the basin by focusing on the **Agrio Formation** that contains the marine strata above the Mulichinco Formation and also has high TOC. We plan to acquire a dataset with the same detail and methodology as we did in the Vaca Muerta Formation to characterize the facies, TOC distribution, geochemical signature, and petrophysical properties of this formation.

Below we provide a list and the detailed description of each project planned for 2021.

2021 Planned Projects

Deep and Shallow -Water Carbonates

- Marine Carbonate Sedimentation in an Active Rift Basin (Red Sea – Gulf of Aqaba)
- Carbonate Contourite Drift Systems
- The Relationship Between Carbonate Slopes and Contour Currents
- Towards a Depositional Model of Coarse-Grained Delta Drift Deposits, Maiella, Italy - Year 2
- Petrophysics of Carbonate Drifts
- Seismic Facies and Stratigraphy of the Yucatan Platform
- Evolution of a Modern Ooid Sand Island - South Joulter Cay, Great Bahama Bank
- Permeability Variations in Cross-Stratified Oolitic Grainstones (Late Pleistocene Miami Oolite)

Carbonate Sequence Stratigraphy

- Carbonate Sequence Stratigraphy in Light of "Standardized Sequence Stratigraphy"
- The Geochemical Expression of Sequence Boundaries

Geochemistry

- A Global Diagenetic Signal?
- Boron, Sulfur, and Clumped Isotopes as Diagenetic Indicators
- Evaluating Drivers of Reefal Transitions Over ~16Myr, Enewetak Atoll
- Application of the Δ_{48} Proxy to the Real World

Petrophysics

- Early Marine Cementation Processes and Velocity Evolution
- Decoding Subtle Diagenetic Alteration: Combining Geochemical and Petrophysical Approaches
- Detecting Pore Types Using Velocity and Resistivity

Unconventional Reservoirs

- Characterization of The Agrio Formation, Neuquén Basin, Argentina
- Virtual Field Trip to the Vaca Muerta Formation, Argentina
- Enhanced Outcrop to Subsurface Correlation in the Vaca Muerta Formation

2021 REPORTING

We will report on our research findings during the year. In a virtual meeting in June we will give a **Mid-Year Progress Report** to inform the Industrial Associates of the status of the projects and the results in hand.

The detailed results of the individual projects will be presented at the **Annual Review Meeting in Miami.** We anticipate an improvement in the Covid-19 situation by the fall and hope that we will be able to meet in person. However, we are still planning to offer a hybrid model, whereby the presentations will be also transmitted simultaneously online. The dates for these two meetings are:

May 18, 2021 – MID-YEAR PROGRESS REPORT

Executive style presentation of the projects and results in hand followed by a discussion. The meeting will be online starting at 9 o'clock in the morning (USA-EST) and 3 pm (UTC+01:00) in continental Europe. The meeting is expected to last about 2 – 3 hours. We will send out a program and other details in April.

OCTOBER 18 - 19, 2021 - ANNUAL REVIEW MEETING

The results of the projects detailed in this prospectus will be presented at the **Annual Review Meeting in Miami, October 18 - 19, 2021**. We will send out information on the logistics for the meeting in the second quarter of 2021.

2021 FIELD SEMINARS

The pandemic prevented the field trip in 2020 that is usually held in conjunction with the Annual Review Meeting. Because there is still uncertainty regarding future travel, details of the meeting field trip, together with other field trips normally offered during the year, are not included here. We will announce these field trips as soon as the situation allows.

COSTS

The contribution of each Industrial Associate towards the research budget is **$55,000**. This contribution complements funding the CSL-CCR receives from national funding agencies such as the National Science Foundation (NSF), the International Ocean Discovery Program (IODP) and other funding agencies. Contributions from our Industrial Associates are mainly used to support students working within the CSL, while funding for the data acquisition, such as seismic and coring expeditions and the funds for new equipment have been made possible by grants from federal funding agencies.

UNIVERSITY OF MIAMI
ROSENSTIEL SCHOOL of MARINE & ATMOSPHERIC SCIENCE

Department of Marine Geosciences
University of Miami

CSL
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CERTIFICATE PROGRAM
APPLIED CARBONATE GEOLOGY

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 of carbonate systems.

OVERVIEW AND COSTS

A Certificate in Applied Carbonate Geology requires the successful completion of 16 course credits assembled from 11 courses in the program (see back). 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 2021. The student/geoscientist will be in residence for 6 months. The current tuition fee is $2,000/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 started in the summer of 2016 and is handled by the Graduate Studies Office of RSMAS.
Registration for the Certificate Program opens each year in June for classes in the following year. Registration is online using the UM-RSMAS graduate program website.

LEARNING OUTCOMES OF THE CERTIFICATE PROGRAM

Learning Outcome 1:

Geoscientists/students will gain a broad knowledge of carbonate geology and geophysics.

Learning Outcome 2:

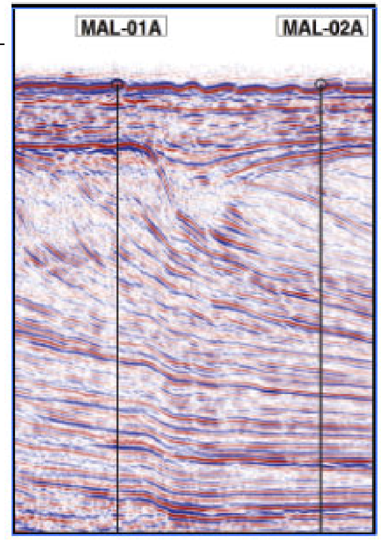
Geoscientists/students will learn to incorporate the acquired knowledge and available data and tools into the workflow of applied projects.

Learning Outcome 3:

Geoscientists/students will learn oral and written communication skills and will be able to communicate their ideas and findings to peers, managers, and administrators.

Instructors In The Program

Gregor P. Eberli	Seismic Sequence Stratigraphy
Peter K. Swart	Carbonate Geochemistry
James S. Klaus	Paleoecology, Geomicrobiology
Donald F. McNeill	Sedimentology, Stratigraphy
Mara R. Diaz	Molecular and Geomicrobiology
Ralf J. Weger	Petrophysics
John Dolson	Carbonate Petroleum Geology
Greta Mackenzie	Petrography
Paul M. (Mitch) Harris	Carbonate Geology



Offered Courses

MGS 611 3 Cr Earth Surface Systems

MGS 641 2 Cr Field Evaluation of Fossil Platforms, Margins, and Basins

MGS 601 1 Cr Seminar in MGS

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 in Carbonate Cores

MGS 789 2 Cr Petroleum Geology in Carbonates

For additional information about the
CSL - Center for Carbonate Research
or the
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Applied Carbonate Geology
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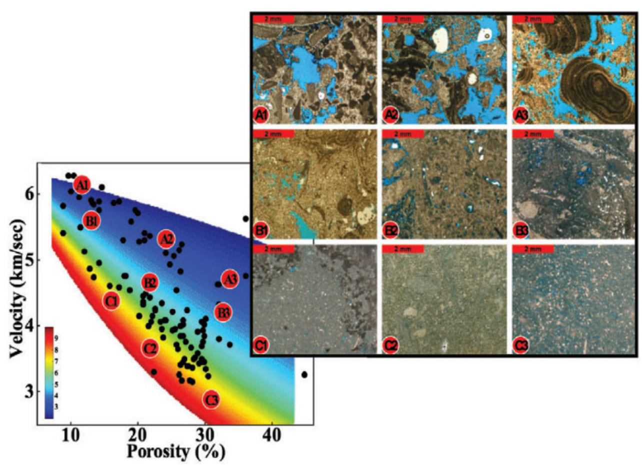

PROPOSED RESEARCH

2021

Marine Carbonate Sedimentation in an Active Rift Basin (Red Sea – Gulf of Aqaba)

Sam Purkis and Paul (Mitch) Harris

Project Objectives

- Develop a rich geophysical dataset for the northern Red Sea capturing the diversity in styles of syn-rift carbonate deposits.
- Examine this dataset to disentangle the varied controls of carbonate deposition through time in an active rift basin.

Project Rationale

Enabled by the 2020 'Deep Blue' research cruise, a comprehensive multibeam dataset is being acquired in late 2020 offshore the Saudi Arabian coastline straddling the coastal shelf to the full depth of the Red Sea spreading axis (Fig. 1). The multibeam bathymetry will be supplemented with sub-bottom lines, ADCP measurement of current systems, and ground-truthed by ROV and submersible dives.

The Red Sea is an active maritime rift system which is unique in the world. Interest in rifts is considerable because they are vital in terms of understanding plate movements and their related seismicity, and because the deep, narrow basins that they yield provide motifs of carbonate deposition that are distinct from more common shelf and open-marine settings (Purkis et al., 2012). Spanning both photic and

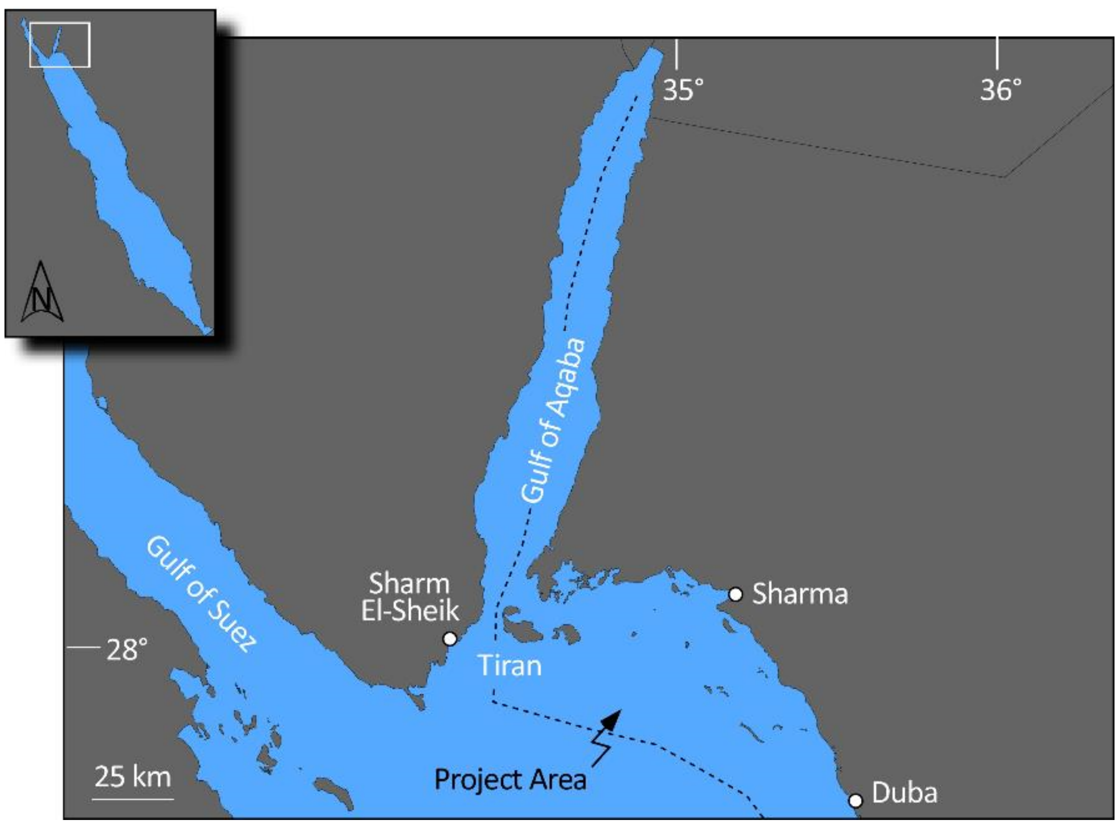

Figure 1: The location of the planned survey of the Northern Red Sea and Gulf of Aqaba.

hemipelagic environments, the deposition of carbonates in the Red Sea is broadly directed by the varied bathymetry delivered by the overall tectonic grain of the rift, and, more locally by pervasive salt tectonics. To the latter, the salt formations likely owe their origin to hydrothermal activity associated with shallow-igneous intrusions along the spreading axis of the basin. Typically associated with fault boundaries, halokinesis in the deep marine presents ductile, glacier-like salt flows which mantle the seabed, much like more conventional gravity flows, plus salt injectites (extrudites) which pierce the seafloor, add to its topography, and disrupt the Pliocene-Quaternary overburden (Mart and Ross, 1987; Mitchell et al., 2010; Augustin et al., 2014). These processes serve to direct the evolution of bathymetry and the subsequent deposition and accumulation of post-salt pelagic and hemipelagic carbonates. The diversity of motifs of carbonate deposition is even more stark in the photic zone. Here, reefal carbonates veneer fault-bounded structural elements of the rift, but also develop atop the pinnacles of salt diapirs. Carbonates deposited on the latter are often abruptly disrupted by collapses of the seafloor created by partial-local removal of mass by salt dissolution and/or suberosion (e.g. Ehrhardt and Hübscher, 2015). Paleo-wind and abundant siliciclastics supplied from the mountains which demark the rift shoulders add further depositional complexity to the syn-rift carbonates. In aggregate, these varied controls acting in the Red Sea deliver arguably the greatest diversity of shore-attached and isolated carbonate platforms witnessed anywhere on the modern Earth. As such, the North Red Sea is an ideal venue to examine syn-rift carbonates and their depositional controls.

APPROACH

A new geophysical dataset will be acquired, ground-truthed, and interrogated to examine the syn-rift carbonates of the northern Red Sea. Emphasis will be placed on disentangling the controls on plan-view morphology and internal stratal patterns of the deposits, with a view to developing a modern analog to Tertiary rift basins in the South China Sea and Mesozoic basins of the South Atlantic.

SIGNIFICANCE

Syn-rift carbonate platform strata can form important petroleum reservoirs within syn-rift basins. They also provide critical records for understanding the tectonic evolution and depositional history of rift systems. This unique dataset from the Red Sea has the potential to provide enhanced understanding in such settings.

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CARBONATE CONTOURITE DRIFT SYSTEMS

Gregor P. Eberli, Sara Bashah and Ralf J. Weger

PROJECT OBJECTIVES

- Continue assembling dimensions and sedimentary characteristics of carbonate contourite systems for a comprehensive data base of such systems.
- Examine the depositional processes of coarse and fine-grained current deposits in carbonates.
- Evaluate the potential of carbonate contourite systems as reservoir and seals.

PROJECT RATIONALE AND GOALS

The increased exploration in deep water has, over the years, triggered research in marine depositional processes other than mass gravity flows. As a result, the importance of bottom currents in deep sea sedimentation is now recognized both on a bed scale (contourite) and on the large sedimentary bodies (contourite drifts) (Rebesco et al., 2014). In addition, case studies document the interaction of bottom currents with mass gravity flows. This interaction has the potential to increase reservoir quality in the siliciclastic deep-water reservoirs as is the case in the giant reservoirs (Coral and Mamba fields) offshore Mozambique. Because bottom currents preferentially move fine-grained sediments, they produce thickness and petrophysical variability in unconventional reservoirs.

The most prolific production from current-controlled strata is in the Upper Cretaceous and Danian chalk fields in the Central Graben of Denmark, where both structural and non-structural trapping mechanisms exist (Megson,1992). In other plays, like coarse-grained distally steepening ramp settings, the current contribution might not have been recognized, fanning the notion that current-controlled deposits are not good reservoirs. It is our working hypothesis that portions of the carbonate contourite drift systems have reservoir potential, although they are generally considered a risky play. A thorough knowledge of these systems is needed to reduce this risk.

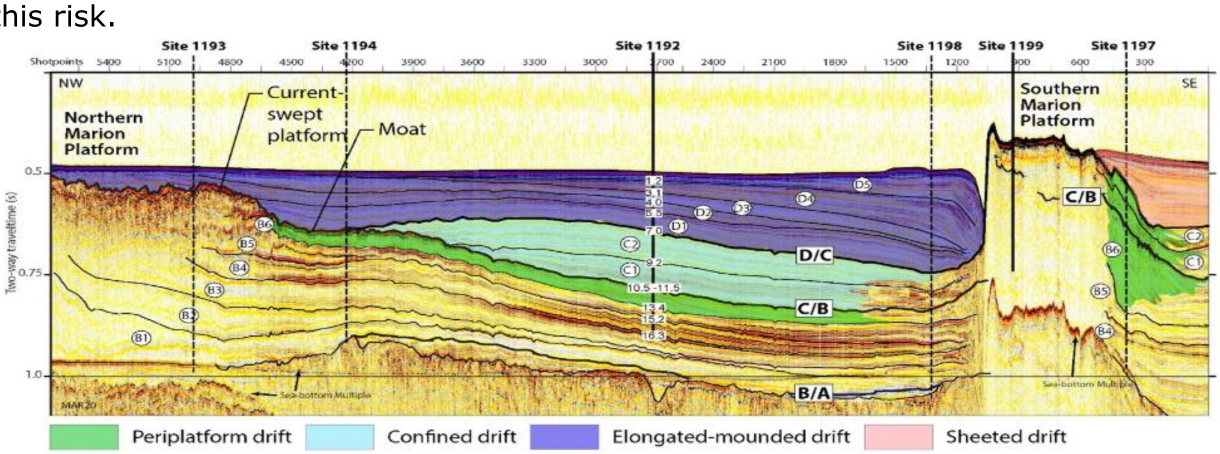

Figure 1: Miocene platforms on the Marion Plateau surrounded by carbonate contourite drifts, illustrating the importance of drift deposition in off-bank areas in the Neogene (from Bashah et al., 2020).

PROJECT PROGRESS AND FUTURE PLANS

For a comprehensive overview of the processes that form carbonate contourite systems, we plan to examine carbonate drifts in various tectonic and depositional settings. In past years, we have described three carbonate-specific types of contourite drifts that develop because of a feedback between steep morphology and sediment production and delivery to the currents (Eberli and Betzler, 2019), and have started to examine the influence of currents on the flank architecture of isolated platforms (Betzler and Eberli, 2019). These studies form the starting point of an evolving data base of carbonate contourite drift systems that includes their dimensions and composition and relates these parameters to the oceanographic setting.

In order to understand the distribution of coarse-grained (potential reservoirs) and fine-grained deposits (seals) within the carbonate drift system, a thorough examination of the depositional processes is needed. These processes will be studied in both the modern and ancient current-controlled settings. A special emphasis will be laid on the conditions that produce supercritical flow and prolonged phases of bedload transport that are likely to produce well-sorted coarse deposits.

Carbonate contourite drift deposits have characteristic log signatures that differ from shallow-water and slope carbonate successions (Giddens et al., 2020). We plan to document and explain these petrophysical properties with laboratory experiments. These results and log data from carbonate drifts will be assembled in a data base.

SIGNIFICANCE

Depositional processes in the off-bank and deep-water areas are the combined product of pelagic fallout, mass gravity flows, and bottom currents. This research will improve the knowledge of the current component on deep water deposition and improve depositional models of slope and ramp carbonates that until recently mostly considered gravity flows to be the main process.

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The Relationship Between Carbonate Slopes and Contour Currents

Sara Bashah and Gregor P. Eberli

Working Hypotheses

- Current strength along carbonate ramps, shelves and isolated platforms determines the
    - dip of the platform flanks
    - dip of the mounded contourite drift
    - grain size of the contourite drift
- Carbonate slopes steepen worldwide in the late Middle Miocene after the onset of modern ocean currents at approximately 13 Ma.

Project Rationale

It has been proposed that carbonate slope architecture is controlled by the amount of deposition, by-pass or erosion of mass gravity flows (Schlager and Camber, 1986) and by the fabric of the slope material (Kenter, 1990). The flanks of carbonate platforms around the world after 13–10 Ma have, however, not only been constructed by mass gravity deposits, but equally by contourites with distinct drift and moat geometries. This style of flank architecture is typical of tropical carbonate platforms growing in the Neogene icehouse world. Ocean currents reduce sedimentation by particle sorting or winnowing and even by eroding slopes (Betzler and Eberli, 2019). In

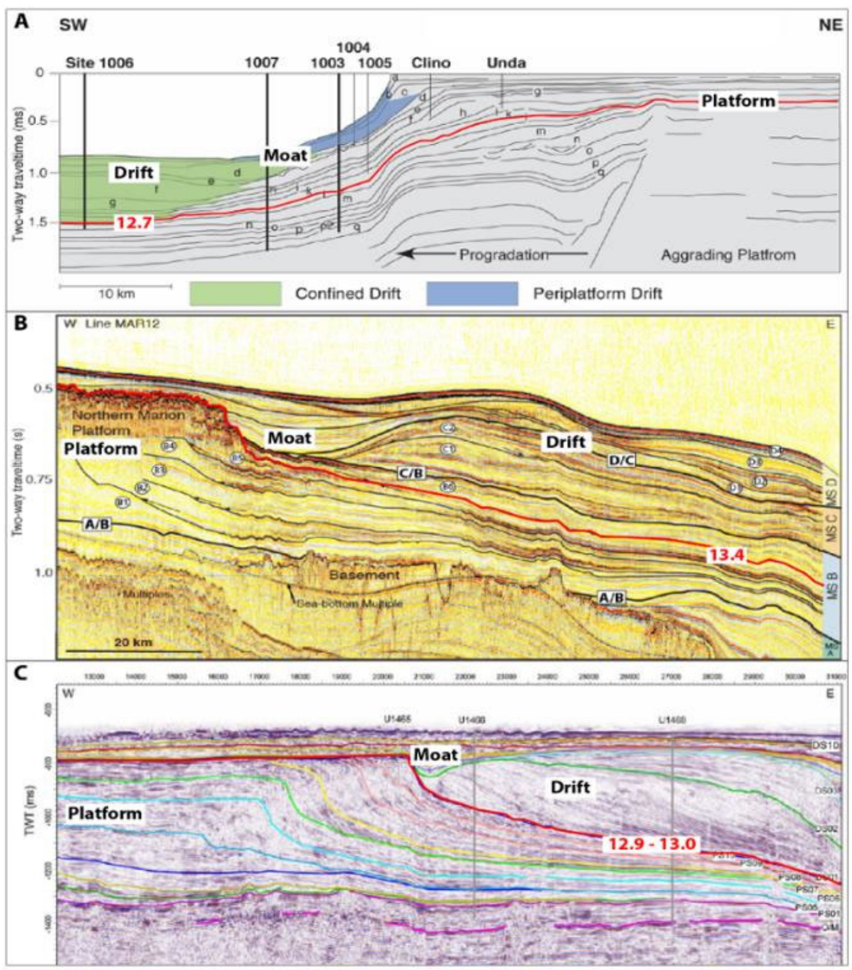


Figure 1: Selected seismic lines from A: Great Bahama Bank, Atlantic. B: Marion Plateau, northeast Australia. C: Maldives, Indian Ocean.

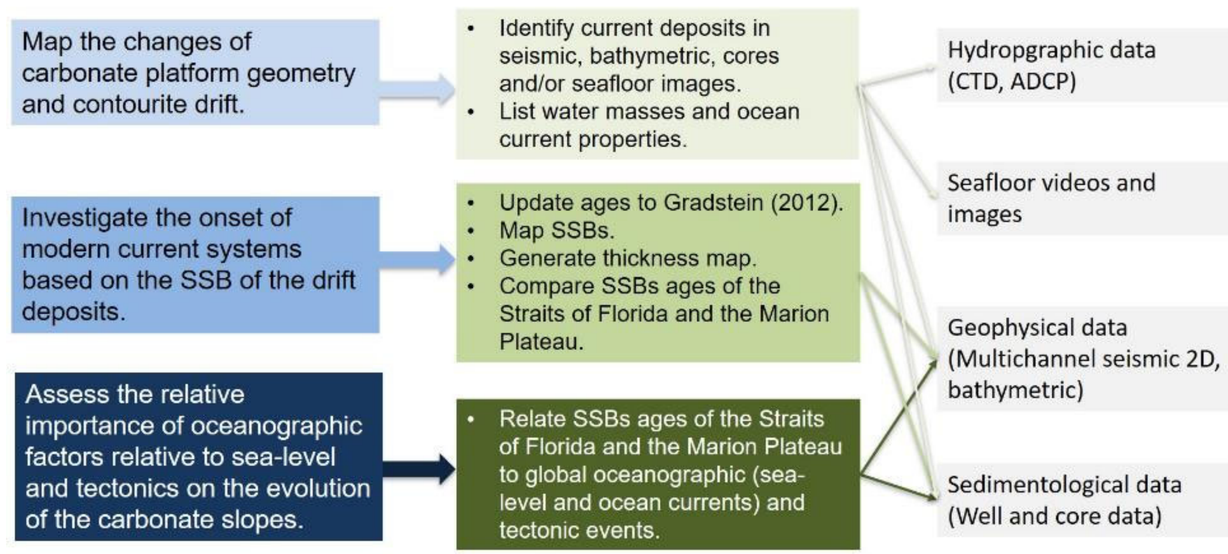
this project we will document the evolution of carbonate slopes in the Bahamas, on the Marion Plateau, and in the Maldives, and their relationship with the along slope sediment transport by contour currents. These platforms show an abrupt onset of current activity along their slopes (Red lines in Fig. 1).

Data Sets

For this study, four data sets consisting of seismic, cores, and log data, from ODP Leg 194, ODP Leg 133, ODP Leg 166, and IODP Expedition 359 are analyzed. Age models are based on biostratigraphy and Sr-isotope dating from these ODP and IODP sites.

Approach and Workflow

To achieve the goals regarding the influence of contour currents on the carbonate platform slopes, we use the following workflow:



Significance

The outcome of this study will improve our understanding of the influence of currents on carbonate platform architecture. The results will prompt a revision of facies models of carbonate platform slopes that have been based mostly on the assumption that they have been constructed by mass gravity flow deposits. This knowledge potentially helps discriminate current-influenced platforms from those evolving during times with less ocean circulation.

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TOWARDS A DEPOSITIONAL MODEL OF COARSE-GRAINED DELTA DRIFT DEPOSITS, MAIELLA, ITALY - YEAR 2

Gregor P. Eberli, Mark Grasmueck, and Ralf J. Weger

PROJECT OBJECTIVES

- Test the hypothesis that stratal succession of the delta drift in the Maiella is the combined product of hyperpycnal flow of a sediment-laden semi-continuous current flowing through the feeder channel and supercritical flow in the adjacent basin.
- Document the proximal to distal facies trends within the delta drift of the Maiella and assess the flow conditions necessary for producing the observed facies distribution.

PREFACE

This project was planned for last year with an approach that combined outcrop work and visualization of the clast distribution in a 3D GPR data set acquired in the quarry of Madonna della Mazza. This visualization portion of the project was completed (Grasmueck et al., 2020) but travel restrictions prevented us from doing the fieldwork, which we plan to complete this year.

PROJECT RATIONALE

The Upper Cretaceous Orfento Formation in the Maiella Mountains (Italy) is a largely mud-free coarse-grained succession of redeposited carbonates with sedimentary structures that are indicative for deposition of subaqueous high-density sediment flows. Yet, the succession does not fit in any of the existing turbidite fan models and recently these deposits have been recognized as a delta drift (Eberli et al., 2019). This carbonate delta drift succession in the Maiella displays characteristics of highly-concentrated turbidity current deposits (Fig. 1). Other elements, like scours filled with pebble- and gravel-sized clasts, and erosive surfaces are typical expressions of transitions from supercritical to subcritical flow (Postma and Cartigny, 2014). Other beds display structures that are associated with hyperpycnal flow. Hyperpycnal flow is commonly associated with sediment laden river water. Yet, isolated carbonate

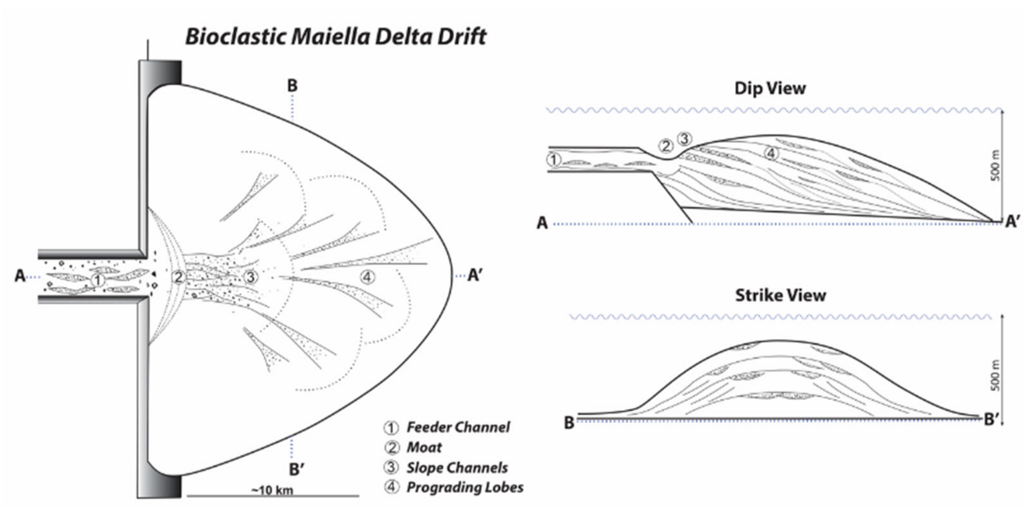

Figure 1: Schematic display of the Maiella drift delta as plan view and dip and strike cross-sections (from Eberli et al., 2019).

platforms do not have fluvial transport and thus, the hyperpycnal flow is likely generated by the ocean current flowing through a feeder channel where it entraps sediment. The large-scale geometry of coarse downlapping lobes in the Maiella delta drift are reminiscent of homopycnal jet outflow typical in Gilbert-type deltas. Thus, it is likely that, depending on the sediment load, both flow mechanisms occur in the delta drift.

PROJECT OBJECTIVES

This project aims to test the hypothesis that a sediment laden ocean current can yield flow conditions to a long-lived homopycnal and hyperpycnal flow, producing the observed bedload transport by the shear provided by the overpassing hyperpycnal sediment laden ocean current (Fig. 2). In addition, hydraulic jumps caused by the topography are thought to produce transitions from subcritical to supercritical flow and several of the observed sedimentary features.

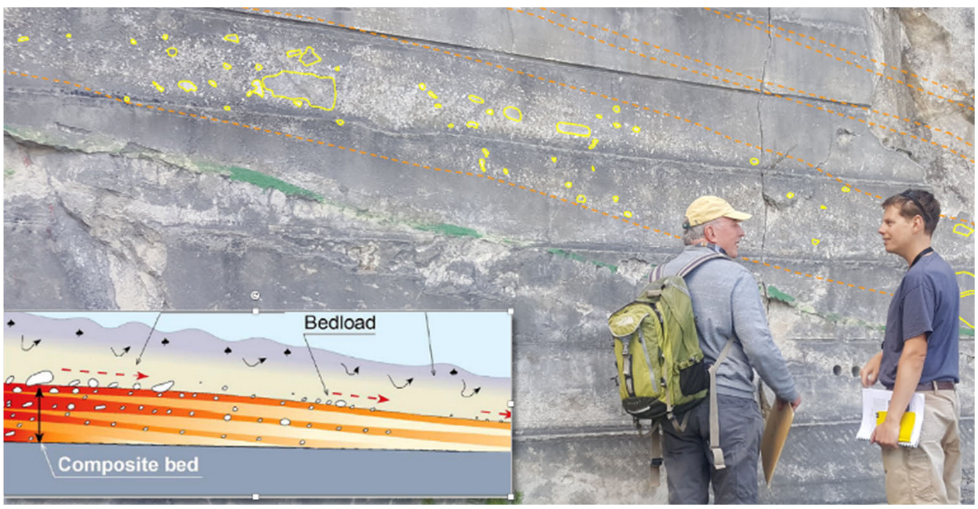

Figure 2: Clast distribution in the Madonna dell Mazza quarry. Clasts appear as white specks in the quarry floor and walls; larger clasts are outlined in yellow. Inset is schematic display of the clasts deposited by hyperpycnal flow (Zavala et al., 2011).

SIGNIFICANCE

This study will provide an assessment of the sedimentologic processes of jet flow generated by ocean currents in feeder channels and their depositional products. The results will identify criteria to distinguish coarse-grained contourite drifts from carbonate turbidite successions.

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PETROPHYSICS OF CARBONATE DRIFTS

Ralf J. Weger, Gregor P. Eberli and Greta Mackenzie

PROJECT OBJECTIVES

- Prepare a data report of the samples from the delta drift in the Maldives.
- Complete the analysis of the petrophysical properties of delta drift deposits in the Maiella.
- Relate log signature of carbonate drift deposits and relate to drift type and mineralogy.
- Produce a catalogue for discriminating logs of slope and basin deposits from carbonate contourite drifts.

BACKGROUND AND PROJECT RATIONALE

For her Ph.D. research, Emma Giddens started to assemble a large data set of laboratory measurements of petrophysical properties of the Miocene delta drifts in the Maldives and Cretaceous drift strata in the Maiella. Photomicrographs of the samples provide information on the grain size and sorting, as well as pore types of these carbonate drift samples. Because of the good sorting in these current-controlled deposits, the correlation between porosity and permeability as well as porosity and velocity are better than in shallow-water carbonates. Likewise, the formation factor m has a narrow range from 1.7 -2.9 (Giddens et al., 2019). The question is, is this unique petrophysical behavior also present in finer-grained carbonate contourite drifts? A preliminary comparison of log data from the coarse-grained delta drift in the Maldives and the confined drift in the Santaren Channel in the Bahamas, reveal

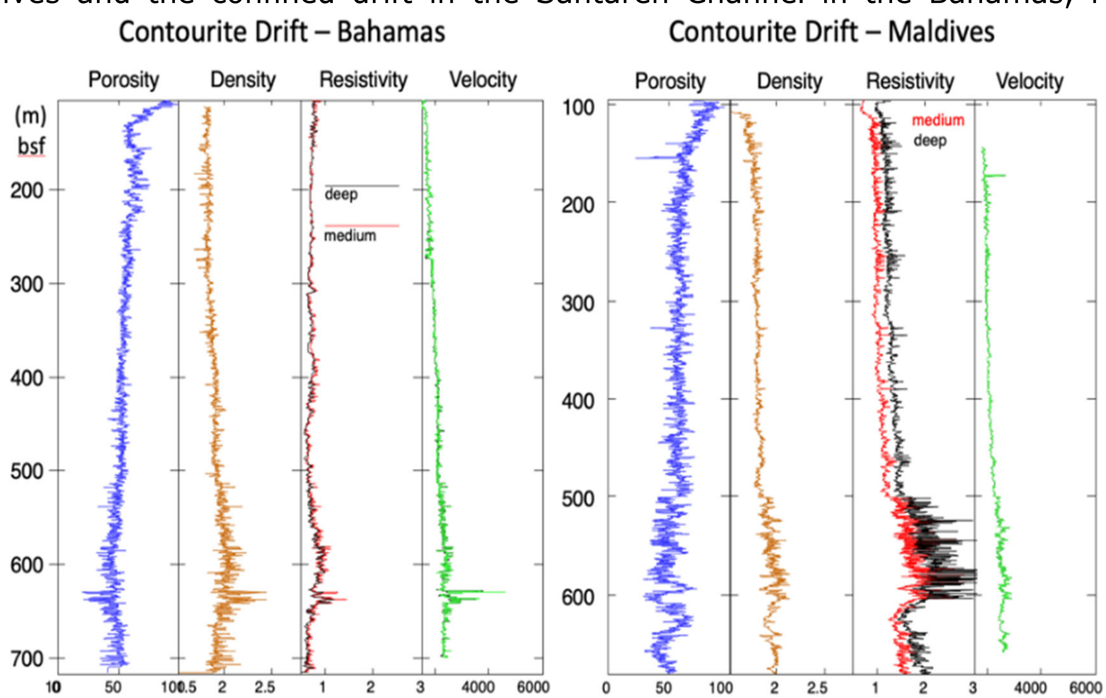

Figure 1: Comparison of logs through the fine-grained Santaren Drift in the Bahamas and the coarser-grained drift in the Maldives. Both log suites show similar log characteristics and a uniform behavior with little variations.

similar log characteristics (Fig. 1). Both logs display little variation in several logs, indicating a generally uniform log signature of carbonate contourite drifts. This project is intended to complete Emma's research with the goal of assembling a comprehensive petrophysical database of carbonate contourite drifts. These data from both laboratory and log will be compared to existing data from prograding slope carbonates to provide guidance for distinguishing petrophysical properties between carbonate contourite drifts and carbonate slope and turbidite packages.

Workplan

Laboratory analyses: Additional samples from the Maiella delta drift will add to the existing data set. In addition, velocity, porosity, resistivity and permeability will be measured on plug samples from drifts on the Marion Plateau in Australia and from the Bahamas. Some of the Marion Plateau samples have been measured in earlier studies by Guido Bracco Gartner (unpublished) and we will request samples from ODP Site 1006 from the Santaren Drift in the Bahamas. The Marion drifts are slightly different in mineralogy as they contain admixtures of siliciclastics and less aragonite than the Maldives and Bahamas drifts.

Petrographic Analysis: From each plug measured, a thin section has been cut for petrographic analysis allowing grain size and sorting to be determined, as well as pore structure to be assessed and associated with the petrophysical measurements. Texture and mineralogy of each sample will be determined, and the pore type of each sample will be analyzed with digital image analysis. SEM imagery will be used to assess the micropore structure.

Log analysis: The log data through the studied drifts were collected by Schlumberger during the ODP and IODP expeditions. These log suites from cores drilled into the three contourite drifts will be used to document the log characteristics of the different drift deposits.

Comparison to slope successions: In all three study sites, contourite drifts are deposited on top of slope carbonates, allowing the petrophysical properties of these two systems to be compared. Kenter et al. (2002) measured the slope sections in the Bahamas and Ehrenberg et al. (2004) assembled the data for the Marion Plateau, while Emma Giddens measured the slope carbonates in the Maldives.

Goal

The goal of this study is to assemble a comprehensive petrophysical database of carbonate contourite drifts. These deposits are potentially either underexplored carbonate reservoirs or seals in the petroleum system.

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Seismic Facies and Stratigraphy of the Yucatan Platform

Elizabeth Guzman and Gregor P. Eberli

Project Objectives

- Assess the tectonic deformation of the Cretaceous portion of the Yucatan Platform and place the evolution of the Yucatan Platform into the regional context of Caribbean tectonics.
- Map the seismic sequences in the intraplatform seaway of the Yucatan Platform.
- Document the influence of the currents on the Neogene deposits on the eastern portion of the Yucatan platform.

Regional Setting and Project Rationale

The Yucatan Peninsula and adjacent shelf form the 350,000 km^2 Yucatan Platform. The platform hosts the Chicxulub impact crater generated by the asteroid that led to the mass extinction at the end of the Cretaceous (Schulte et al., 2010). The asteroid impact deformed the underlying basement and created a multi-ring crater that is 200 km in diameter. Scientific drilling penetrated the post-impact carbonates, an ~ 130 m thick sequence of impact strata and shocked and fractured basement rocks (Gulick et al., 2016). Regional seismic data reveals that the impact crater is located within a large N-S trending depression – the Intra-platform Yucatan Basin (Fig. 1; Guzman et al., 2019).

The Cretaceous strata displays faults and deformation that are reminiscent of wrench faults. The question is how much of this deformation is the result of the asteroid impact and how much is related to changes in the regional stress regime? The boundary between the Cretaceous and Paleocene strata is a well-defined seismic horizon. The Yucatan Basin that houses the impact crater is filled with prograding clinoforms, probably starting as early as the Early Eocene (Whalen et al., 2013, Canales-García et al., 2018).

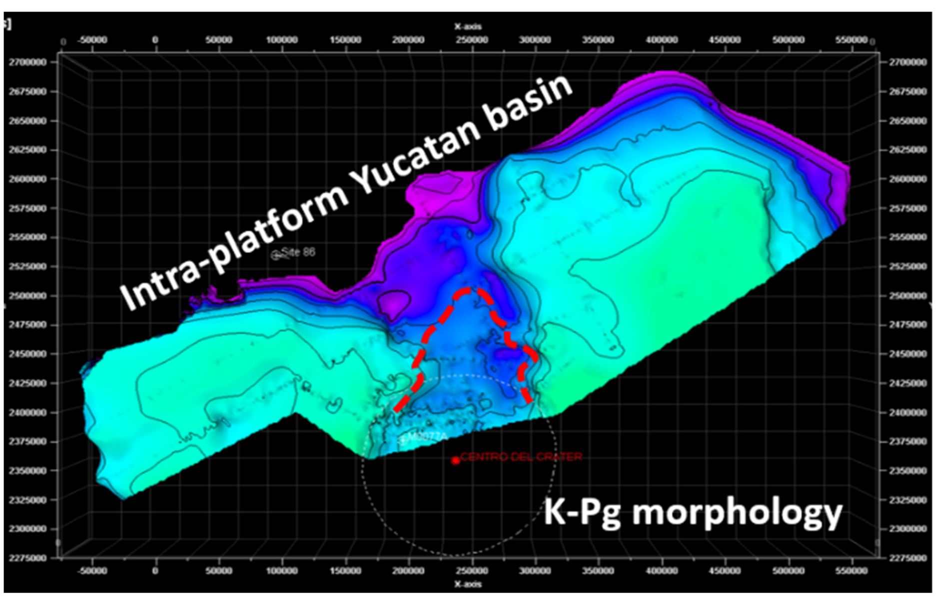

Figure 1: Topography of the Yucatan Platform at the Cretaceous-Paleogene boundary, displaying the roughly north-south oriented Intra-platform Yucatan Basin, which is nearly 180 km wide and up to 1200 m deep (from Guzman et al., 2019).

This project aims to a) assess the structural evolution of the Yucatan Platform, b) analyze the prograding sequences with regards to sea-level control, and c) evaluate how many of the prograding clinoforms at the eastern fringes of the Yucatan Platform are influenced by the Yucatan Current that today flows across this area. A comparison of the timing and style of the deformation and the infill of the intraplatform basin are strikingly similar to the deformations observed in Great Bahama Bank and the Straits of Andros that are also filled with prograding clinoforms. We plan to compare and contrast these two areas.

Data Set and Workplan

The seismic data in hand consists of seismic lines collected in conjunction with the IODP drilling of the impact crater, older data collected by the University of Texas, and newer data from the National Hydrocarbons Information Center (CNIH) in Mexico. In addition, we expect to secure more seismic data from CNIH in Mexico to cover crucial areas for our study goals.

We plan to build a robust seismic stratigraphic framework of the Yucatan Platform that relies on the ages acquired by dating material provided by existing onshore and offshore cores. Faults and deformation will be mapped within this framework and placed into the larger regional context. A detailed sequence stratigraphic analysis will be performed in the prograding sequences that fill the intraplatform basin. Results of the sequence analysis will be compared to timing and style of the prograding clinoforms in the Straits of Andros within Great Bahama Bank.

Significance

The Yucatan Platform is a large and important – yet underexplored - carbonate platform within the Caribbean. It also offers the opportunity to investigate the consequences of a large impact on the deformation and subsequent recovery of a carbonate platform.

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Evolution of a Modern Ooid Sand Island - South Joulter Cay, Great Bahama Bank

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[1)] *Texas A&M University*
[2)] *Chevron Energy Technology Company*

Project Objectives

- To complete acquisition of high-resolution drone imagery and a DTM for better delineation of the morphology of Holocene ooid sand ridges forming South Joulter Cay (SJC) allowing a detailed interpretation of the processes that formed the island.
- To further calibrate the timing of key depositional events within the island's history by select radiometric dating.

Project Rationale

The Joulters ooid sand body covers some 400km^2 of Great Bahama Bank north of Andros Island. It is famous as a site for the study of high-energy carbonate sediments and is a central analog for understanding oolitic grainstone reservoirs due to the clearly observable interplay between vast stabilized sand flats and active ooid bars (Harris, 2019). The geological story of the three Joulter Cays (low lying islands), however, deserves equal attention. The Joulter Cays, built of lightly cemented oolitic and peloidal sediments, form along the eastern, windward-facing margin of the ooid sand body. Previous field mapping and local coring placed island development within the story of sand body development and established they are a very recent feature with radiocarbon dating showing ages from ~2000 ybp to present (Harris, 1979). These islands, while small in areal extent, act to extensively modify the distribution of energy across the top of the Joulters sand body, blocking wave energy from the open ocean to the east, and confining tidal flow to the channels that lie to the south, the north, and between each island (Fig. 1). This aspect of an energy barrier introduces a sudden shift towards muddy facies in the immediate lee of the islands and isolates ooid production to tidal channels and their associated ebb and flood lobes.

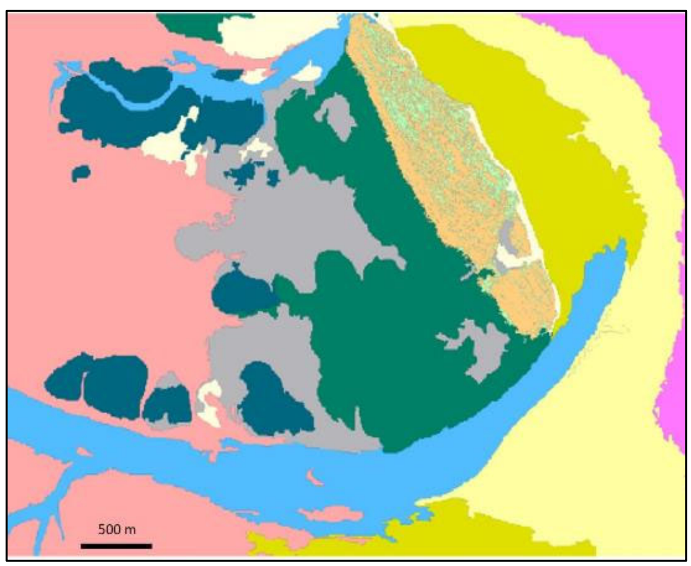

Figure 1. Facies map for SJC and surroundings. The island is bounded at the south by the largest and deepest tidal channel observed within the Joulters sand body and fronted by an active ooid sand shoal. Variably vegetated muddy sandflats develop on the lower energy, lee side of the island. Map generated by Purkis Partnerships Ltd for Chevron ETC.

Approach

Our ongoing examination of SJC, the largest of the islands, targets a better delineation of the timing and processes that formed the island. High resolution imagery and a DTM constructed from a drone survey improve on previous maps. Historically, SJC records a period of higher ooid accumulation rate than occurs locally in the sand body today; ooid sand production was greater than the system's ability to hydrodynamically redistribute these sediments. Ridge topography on the island suggests that active sand bars locally built to beaches and back-beach dune ridges formed repeatedly. A scenario for island development based on existing data (Fig. 2) emphasizes growth stages reflecting variations in dispersal of ooid sands by tidal channels, wind and wave energy, and longshore and storm-related currents. Topographic profiles extracted from the DTM show that higher than average beach ridges are associated with the initiation of each of the island's growth stages, suggesting that the island's morphological evolution is closely integrated into the wider evolution of sediment generation and transport within the overall sand body.

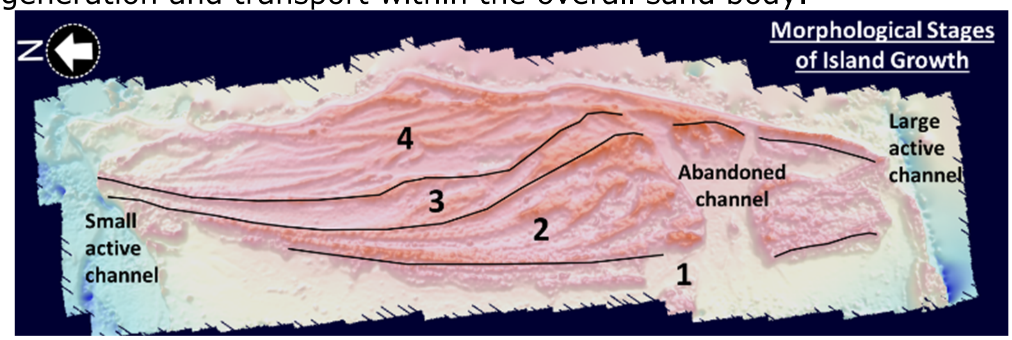

Figure 2. DEM of South Joulter Cay showing and describing growth stages based on ridge morphology.

SIGNIFICANCE

This study focuses specifically on the process by which a key facies transition occurs, namely the nucleation and growth of islands within accommodation-restricted sand bodies. It has particular impact on facies interpretation and correlation within subsurface grainstone reservoirs as well as the interpretation of their sequence stratigraphic and diagenetic development. The islands, and SJC in particular, introduce a new suite of Holocene facies (beach, back-beach storm ridges, tidal flats) into the dominantly subtidal record of the overall sand body. Their presence also armors the sand body at its most energetic margin and the topography of the islands significantly influences the local water movement and thus depositional patterns. As such, the most recent geologic record shows a facies transition that, if seen out of context, may be misinterpreted as being caused by a sudden increase in water depth, when the truth is exactly the opposite. The development of islands like Joulters also introduces an element of spatially constrained meteoric diagenesis (cementation and dissolution) contemporaneous to sand generation and deposition (Halley and Harris, 1979).

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Sediment Transport on The Great Bahama Bank - Insights from Fair- & Storm-Weather Conditions

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Project Objectives

- To assess the sediment budget of Great Bahama Bank (GBB) via quantification of sediment production, transport, and on- and off-platform accumulation.
- To evaluate the balance between fair and storm-weather conditions on sediment transport.
- To quantify volumetric sediment loss from the platform top via analysis of off-margin geophysical data.

Project Rationale

Recent GBB studies have primarily focused on either platform sediment production, mapping of on- and off-platform sediment distributions, or analyzing the variable filling of accommodation space. The platform's sediment budget has received little attention, which is the motivation for this project. SLIM hydrodynamic modelling (developed at UCL, Belgium) indicates that fair-weather conditions do not deliver sufficiently vigorous current velocities to resuspend meaningful volumes of sediment. By contrast, storm conditions do. Analysis of satellite-derived turbidity data suggest a seasonal cycle to sediment lofting, upon which storms overprint (Fig. 1).

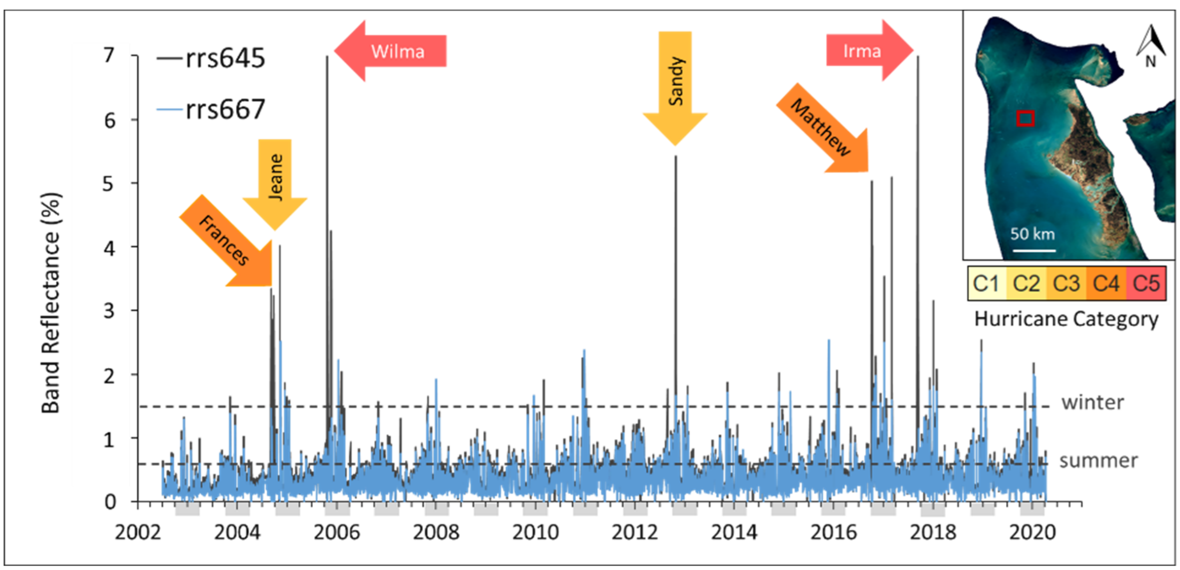

Figure 1. Timeseries of 645 and 667 nm MODIS reflectance on a portion of GBB (location map, top right). Elevated 667 nm reflectance (blue line) suggest seasonal variability in suspended sediment attributed to the passage of winter cold fronts (winter = gray bars beneath x-axis). Elevated 645 nm reflectance values (black line) capture storm-induced lofting of seabed sediment. Major hurricanes and respective categories labeled with colored arrows. Data courtesy of Brian Barnes (USF).

The question remains, however, as to how much of the GBB sediment budget is resuspended and redeposited in proximal (on-platform) locations, versus distal locations, over the platform margin in deep water. Thick accumulations of sediment sourced from the platform top have been recognized on the western flanks of GBB, and these deposits show substantial along-strike variability in their thickness and sedimentary facies (Anselmetti et al., 2000; Mulder et al., 2012). Deciphering the relative contributions of fair- versus storm-weather processes to the overall sediment budget is an important step in understanding the drivers of facies heterogeneity on this platform and its ancient analogs. Building forward from the substantial research conducted by our CSL collaborators past and present, we aim to quantify the relationship between prevailing hydrodynamics and sediment production, transport, and accumulation.

APPROACH

Satellite-derived turbidity products will be compared to model simulations capturing fair- and storm-weather conditions in order to estimate suspended sediment volumes. Off-platform suspended sediment volumes will then be compared to CHIRP sub-bottom lines acquired off the western GBB margin. This analysis will inform on the volume of sediment which has been lost from the platform top and accumulated on its margins, or else has been completely lost from the system.

SIGNIFICANCE

Intimate knowledge of sediment production and water movement atop the GBB is paramount to understanding the volumetric significance of sediment dispersal. Both processes impose physical limits on platform development. Overall, the investigation of sediment production, transport, and accumulation in a hydrodynamic context allows for a novel carbonate source-to-sink analysis.

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PERMEABILITY VARIATIONS IN CROSS-STRATIFIED OOLITIC GRAINSTONES (LATE PLEISTOCENE MIAMI OOLITE)

Donald F. McNeill

PROJECT OBJECTIVES

- To conduct whole-core constant-head hydraulic conductivity measurements on outcrop cores of cross-stratified Late Pleistocene barrier bar facies of the Miami Oolite to assess the range and variability of matrix porosity.
- To provide a flow comparison to solution-enhanced (touching vug) ichnogenic-influenced permeability of the burrow-mottled oolitic pack/grainstones of the tidal shoal complex.

PROJECT RATIONALE

That interest in porosity and permeability of oolitic grainstone still exists can be attributed to both the variability of depositional lithofacies and diagenetic evolution (Harris and Purkis, 2020; Goodner et al., 2020). Harris and Purkis (2020) maintain that the Late Pleistocene Miami Oolite is representative of a grainstone-rich unit that has been surficially karsted and can be used as an analogue for similar units with high permeability. They report that both marine facies and early meteoric diagenesis can impart a potentially long-lived control on fluid flow properties as related to heterogeneity. Two main motifs have long been recognized in the Miami Oolite (Fig. 1) and Harris and Purkis (2020) summarize these as the dip-oriented, tidal bar belt of shoals and shallow channels, and a strike-oriented barrier bar that lies just seaward of the tidal bar belt. The tidal bar belt is commonly burrow mottled packstone/grainstones, whereas the barrier bar (35 km long by 1 km wide, Harris and Purkis 2020) is largely cross-stratified grainstone with lesser, burrowed grain/packstones. From a flow standpoint, the most significant impact is from solution-enhancement of the burrowed facies that leads to touching-vug macropores within a host sediment with matrix pores. Flow is, however, dominated by the touching vug macropores that formed by solution-enhancement of the early burrows (Cunningham et al., 2009).

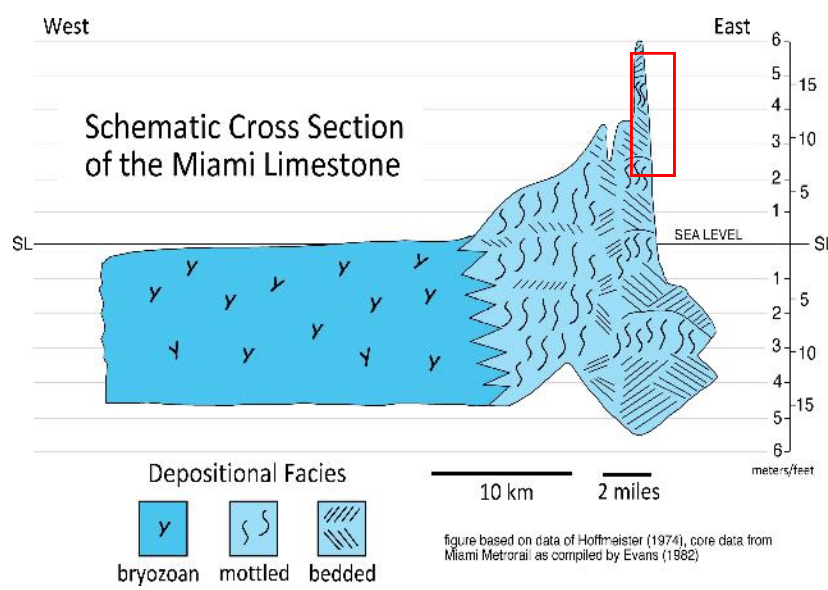

Figure 1. Generalized depositional facies for the Miami Oolite tidal shoal and bar complex. This study will focus on the cross-stratified barrier bar deposits along the eastern side of the geobody.

APPROACH

The unit of interest is the Late Pleistocene Miami Oolite (~120 ka), that crops out throughout the greater Miami area. The formation is well studied from the standpoint of the depositional facies, lithology, petrography, sedimentary structures, and diagenesis (Hoffmeister et al., 1967; Halley and Evans 1983; Neal et al. 2008). Parts of the Miami Oolite, generally the burrow-mottled facies, have been well characterized (porosity, permeability) as part of the main drinking-water aquifer (unconfined Biscayne Aquifer) for southeastern Florida. However, flow characteristics of the cross-stratified components (mainly along the eastern barrier bar lithofacies) where matrix flow is dominant has been less studied (Truss et al., 2007; Neal et al., 2008). This is especially true at the bed scale where distinct lithologies occur (e.g. coquina beds at crossbed bounding surfaces) that may influence flow. Several outcrop cores of cross-stratified barrier bar facies, some already collected, will be used for whole-core constant-head hydraulic conductivity measurement (Fig. 2). Core sections up to 50 cm in length will be first analyzed and then sub-sectioned in ~10-15 cm intervals to assess the intra-bed scale variability. A constant-head measurement technique will be used to determine hydraulic conductivity and data will be collected for 4-6 days to allow for full water saturation and flow stabilization. This multi-day flow profile is usually consistent with, and characteristic of the pore types within the bedded oolite.

SIGNIFICANCE

The cross-stratified barrier bar component of the Miami Oolite, an excellent reservoir analog, makes up a significant part of the whole oolitic geobody. The barrier bar component has a predictable geometry (elongate) and orientation relative to the shoal and channel component. Several studies (Harris and Purkis, 2020 and Goodner

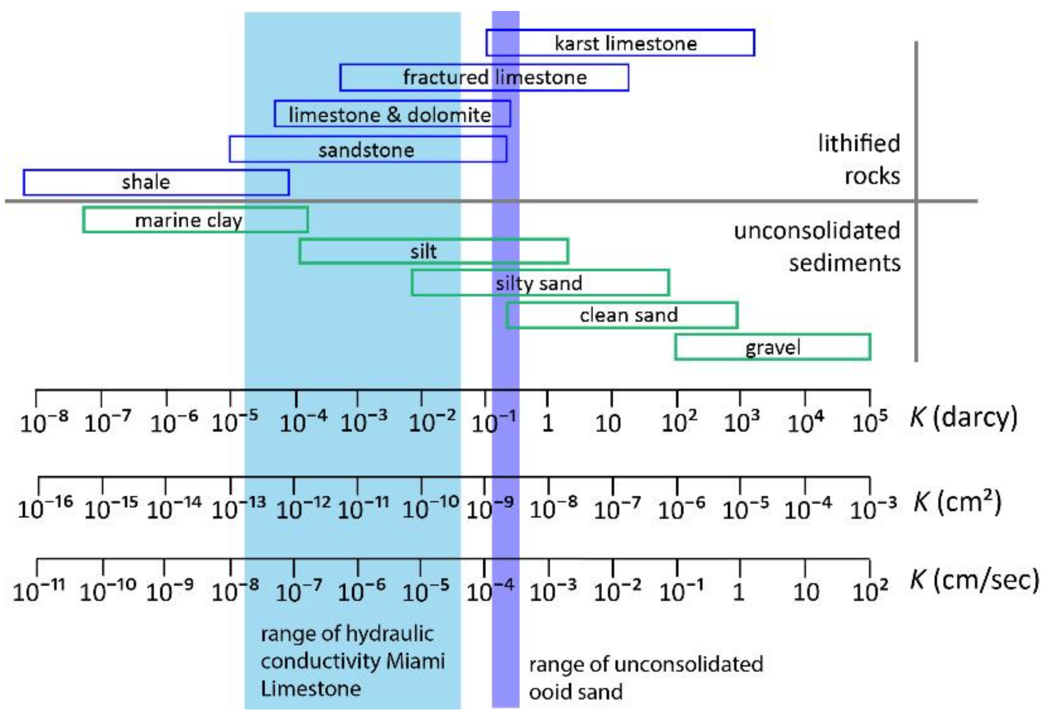

Figure 2. An initial comparison of unconsolidated ooid sand (purple) with preliminary values of the Late Pleistocene Miami Oolite (blue shaded).

et al. 2020) suggest that original sediment texture (grain size, sorting) and early diagenesis have long-lived controls on porosity and permeability even after burial and compaction. Deposition of cross-stratified ooids sand and subsequent meteoric diagenesis (interparticle cementation and ooid dissolution) has produced a predominantly matrix-type pore system (inter- and intra-particle porosity). Goodner et al. (2020) in their study of multi-aged oolitic grainstones have found the pore attributes and permeability are better correlated with grain texture than with cementation and compaction. This study will provide a dataset of hydraulic conductivity values (converted to permeability) that evaluates the flow properties of ooid grainstones that retain both original depositional bedding and the influence of early, pre-burial meteoric diagenesis.

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CARBONATE SEQUENCE STRATIGRAPHY IN LIGHT OF "STANDARDIZED SEQUENCE STRATIGRAPHY"

Gregor P. Eberli

PROJECT OBJECTIVES

- Evaluate how the accommodation succession method (Neal and Abreu, 2009), as well as the stratigraphic surfaces method of Catuneanu et al. (2009), can be reconciled with unconformity-based carbonate sequence stratigraphy.
- Interrogate seismic and outcrop data if surfaces relevant for sequence stratigraphy fall into the same position in a base-level cycle in carbonates as proposed in the siliciclastic depositional models.

PROJECT RATIONALE

Sequence stratigraphy originally was based on the principle of subdividing a succession of rocks into sequences by unconformities and the correlative conformities (Mitchum et al., 1977). This unconformity-based method has been proven to be robust for giving the sequence boundaries chronostratigraphic values, but it has been increasingly replaced by two methods that focus on the stacking of the strata. The accommodation succession method uses the stacking pattern of the genetically related successions to define sequences. A key assumption of this method is that the building blocks in a sequence form in response to varying rates of coastal accommodation increase and decrease (δA) relative to the rate of sediment flux (δS) (Neal and Abreu 2009).

The second method that claims to provide a "standardization of sequence stratigraphy" subdivides the stratigraphic succession into a succession of genetic units (forced regressive, lowstand and highstand normal regressive, transgressive;

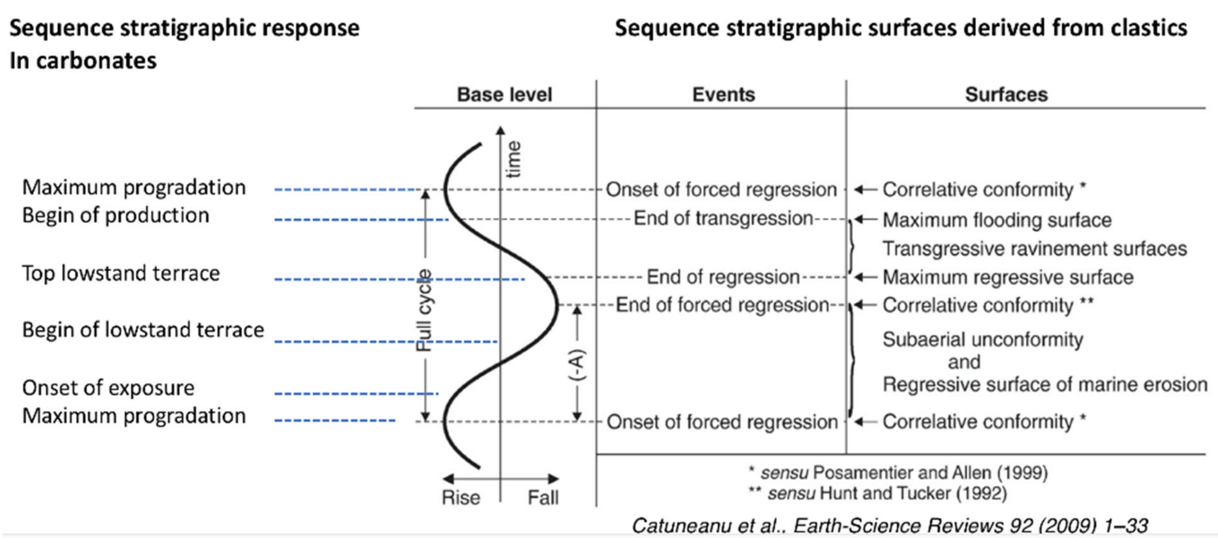

Figure 1: Comparison of response to the four events of the base-level cycle for shallow-water carbonates (left) and clastics (right from Catuneanu, 2006) and the timing of seven surfaces of sequence stratigraphy in this model and cores together with log information. The different response of the two systems and the implication for sequence stratigraphy will be explored in this project.

i.e. systems tracts) bounded by sequence stratigraphic surfaces (Catuneanu et al., 2009).

Both methods rely on the sedimentary response of the siliciclastic depositional system to base-level variations for the stratigraphic analysis and interpretation (Fig. 1). Anchoring the sequence stratigraphy on the clastics system is a necessary challenge if the methodology is to be applied to carbonates and mixed systems. Neal et al. (2016) acknowledge that in carbonate environments the accommodation succession method "can be used with caution and recognition of the complexities of carbonate sediment production and distribution rates relative to changes in rate of accommodation creation". Catuneanu et al. (2009) on the other hand conclude that the difference in carbonate systems lies only in the physical character of stratigraphic surfaces and the sediments they subdivide. Many carbonate geologists consider this conclusion as premature and untested. This project plans to test the two newer methods in carbonates by applying the two methods to carbonate successions in seismic data and in outcrop.

APPROACH

Sequence stratigraphic analyses with the three above-mentioned methods will be performed in carbonate successions. The results will be compared and interrogated regarding the implications for building sequences with these three methods in carbonates. Likewise, the formation of stratigraphic surfaces during a cycle of base-level changes will be examined in carbonates and compared to the proposed surfaces forming in clastic systems (Fig. 1). These analyses will be conducted in sites in tropical environments, cool-subtropical areas and cold-water carbonates.

GOAL AND SIGNIFICANCE

This project intends to reconcile the new methods in sequence stratigraphy with unconformity-based sequence stratigraphy and assess which elements can be incorporated in carbonate sequence stratigraphy and which are not suitable for the carbonate system. Such an interrogation is crucial for accurate interpretation of carbonate sequences using the new methods.

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THE GEOCHEMICAL EXPRESSION OF SEQUENCE BOUNDARIES

Peter K. Swart, Greta J. Mackenzie, Amel Saied, Amanda M. Oehlert, and Gregor P. Eberli

OBJECTIVE

- To examine the geochemical expression of sequence boundaries.
- Complete the stable C and O isotopic and XRD analysis of the carbonates.
- Conduct stable C isotopic analysis of the organic material from the Bahamas Transect (ODP Sites 1003-1007) and the Clino and Unda cores.

KEY POINTS AND PROJECT DESCRIPTION

Sequence boundaries record changes in sediment/rock related to changes in sediment source and/or diagenetic history. As such, sequence boundaries can have varying geochemical expressions as regards their C and O isotopic composition and mineralogy. The Bahamas transect offers a valuable opportunity to test these expressions and we will focus on increasing the resolution of the existing geochemical analyses. An important consideration is to obtain a high enough spatial resolution of samples and although over 10,000 samples have been taken from the five Ocean Drilling Program (ODP) sites (1003-1007) and the Clino and Unda cores which form the Bahamas Transect, only ~ half of these have been analyzed for $\delta^{13}C$ and $\delta^{18}O$ of the carbonate and a much lesser amount for the $\delta^{13}C$ of the organic material. This project aims to complete these analyses and apply the results to understanding the geochemical expression of the boundaries.

PRELIMINARY RESULTS

We have completed the $\delta^{13}C$, $\delta^{18}O$ and X-ray diffraction analyses of the Unda and Clino cores. Much of these data have already been published (Melim et al., 2001; Oehlert et al., 2012; Oehlert and Swart, 2014; Swart and Oehlert, 2019). Recently completed analysis of the $\delta^{13}C$ values of the organic material from the Unda core will be presented at the 2021 annual meeting. While the initial study of the $\delta^{13}C$ variations in the Leg 166 samples showed similarities between the $\delta^{13}C$ values of the individual sequences between the various sites (Swart and Eberli, 2005), the resolution of the sampling was insufficient in some cases to clearly identify geochemical signatures at the boundaries. We are in the process of adding a significant number of C and O isotope analyses in all the cores and will add XRD analyses and measurements of the $\delta^{13}C$ of organic material in the upcoming year. An example of the increased resolution of the analyses can be seen in Figure 2 which compares the database used in Swart and Eberli (2005) (red symbols) with the additional samples which we have analyzed (blue) for Site 1003. The grey bars indicate the position of the sequence boundaries (Eberli, 2000). Based on the known occurrence of negative $\delta^{13}C$ values along disconformities, these new data will allow the position of the boundaries to be more accurately defined. These high-resolution data and the geophysical logs used in conjunction with rolling window regression will improve interpretation and understanding of diagenetic events and the formation of sequence boundaries.

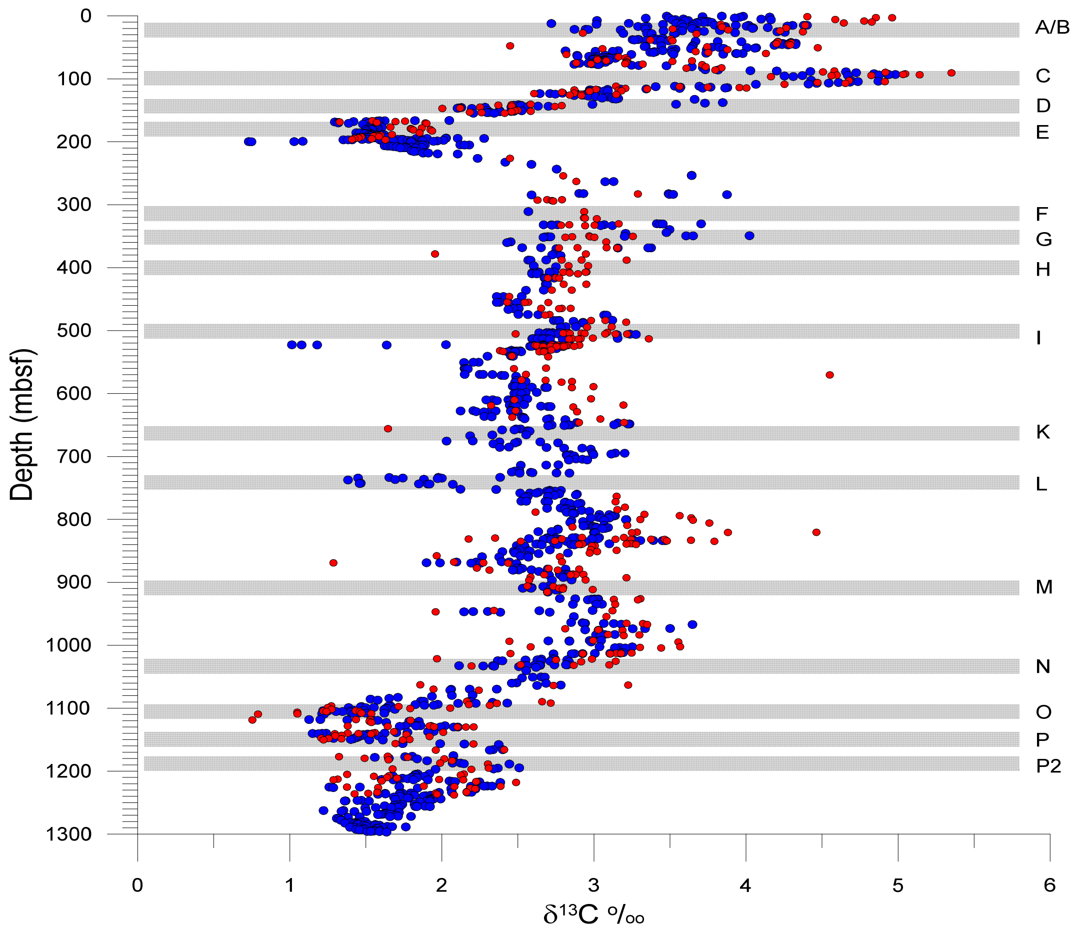

Figure 1: Data from Site 1003 previously published (Swart and Eberli, 2005) (red) and recently analyzed data (blue) together with the sequence boundaries (Eberli, 2000) which below 400 mbsf coincide with negative changes in the $\delta^{13}C$ values. Additional data allows the repositioning of several sequence boundaries.

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A GLOBAL DIAGENETIC SIGNAL?

Megan Smith, Colleen Brown, Evan Moore, Peter K. Swart, and Amanda M. Oehlert

OBJECTIVE

- To construct a high resolution, multiproxy geochemical record of cores from Enewetak Atoll in the Pacific Ocean.
- To compare with the Great Bahama Bank sediment core records in the Atlantic Ocean basin.
- To ascertain whether shallow-water carbonates can express a global diagenetic signal.

KEY POINTS AND PROJECT DESCRIPTION

We have initiated a geochemical comparison between Pacific (Enewetak) and Atlantic (Bahamas) shallow-water sediment cores to identify globally recorded $\delta^{13}C$ and $\delta^{18}O$ values indicating meteoric diagenesis. Initial clumped isotope analysis and mineralogy have also been examined, indicating diagenetic surfaces and recrystallization in both regions. We also plan to analyze the $\delta^{13}C$ and $\delta^{15}N$ values of the organic material, finish clumped isotope and mineralogical analysis, as well as preform trace element analysis on all of the Enewetak sediment samples. All geochemical data will be assessed using Rolling Window Regression (RWR) to identify and confirm regions of diagenetic alteration in the core records (Oehlert and Swart, 2019). The data from Enewetak will be compared to similar data from the Bahamas and other locations, where available.

PRELIMINARY RESULTS

- The $\delta^{13}C$, $\delta^{18}O$, and mineralogy data from Enewetak sediment cores indicate regions of meteoric diagenesis resulting in negative isotope excursions and recrystallization of aragonite to calcite, in several regions throughout the core.
- Initial comparison between Enewetak and the Great Bahama Bank sediment cores show similar negative carbon isotope trends towards the surface (Fig. 1), indicative of meteoric diagenesis. The presence of this signal in both regions indicates a global diagenetic process which results in global systematic overprinting of the original isotopic signal.
- This initial evidence indicates that periods of extensive sea-level change will be recorded within shallow water carbonate sediments, providing an opportunity to evaluate major diagenetic events in earth's past, recorded within the sediment records.
- Utilizing newly analyzed geochemical data paired with the RWR analysis will allow for high resolution identification of diagenetic signatures, furthering our understanding of the influence and relationship global diagenesis has on a variety of isotopic proxies.

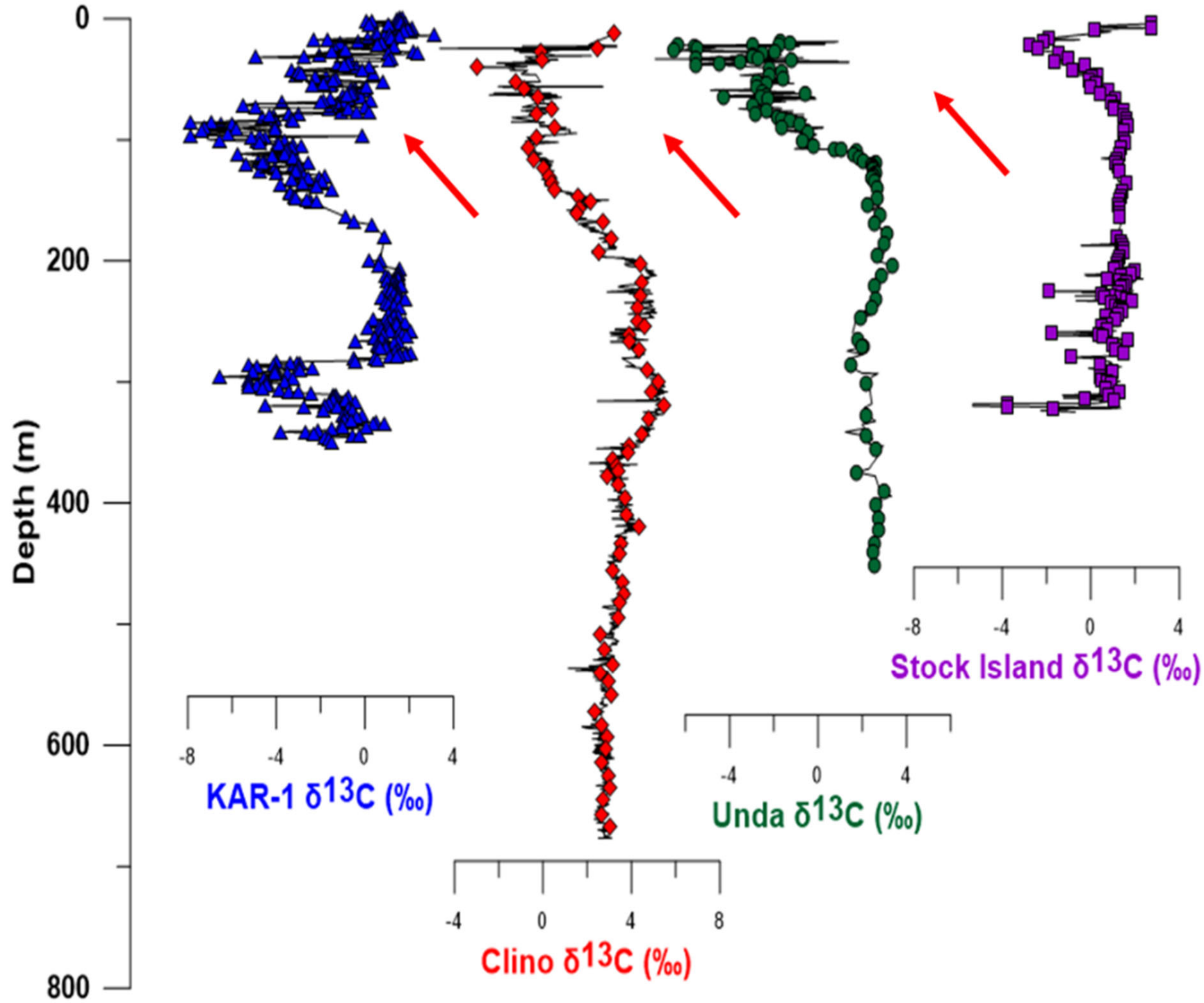

Figure 1. Carbon isotope data comparison between Enewetak core KAR-1, GBB cores Clino and Unda (Melim et al., 2001; Oehlert and Swart, 2014), and Stock Island core (Melim et al., 2004). Red arrows show isotopic resetting trends of meteoric diagenesis in all cores.

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BORON, SULFUR, AND CLUMPED ISOTOPES AS DIAGENETIC INDICATORS

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KEY POINTS AND PROJECT DESCRIPTION

- Conduct boron, sulfur, and clumped isotopic analyses of carbonates from the Bahamas, Enewetak, and various ODP, IODP, and DSDP sites that have experienced meteoric and marine diagenesis.
- Combine these with traditional geochemical indicators of diagenesis such as $\delta^{13}C$ and $\delta^{18}O$ values to better define the sedimentological systems with respect to temperature, pH fluctuation, and bacterial sulfate reduction.
- Compare data from Clino to similar geochemical data of Enewetak Atoll to constrain the global influence of diagenetic resetting on sedimentological records.

OBJECTIVE

This project will construct a high resolution, multiproxy geochemical record of cores from the Great Bahama Bank in the Atlantic Ocean basin and compare this data with sediment core records from Enewetak Atoll in the Pacific Ocean. The aim of this

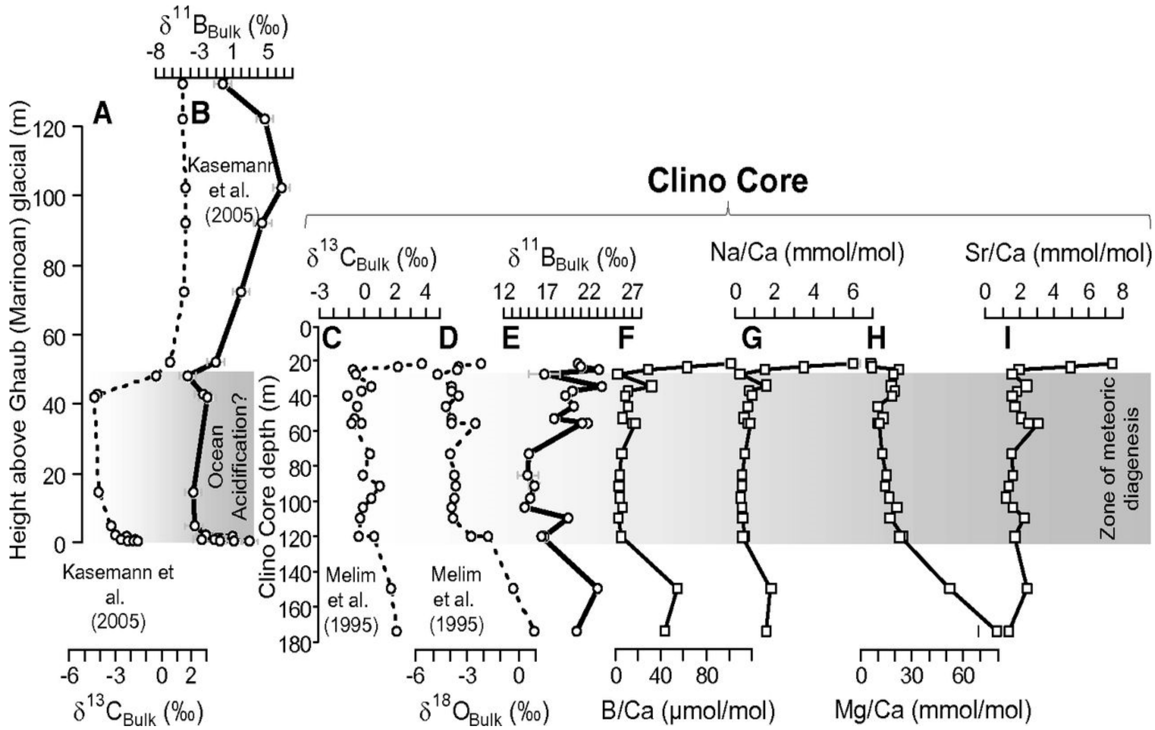

Figure 1. Comparison of $\delta^{11}B$ and $\delta^{13}C$ values from rocks deposited after the Marinoan glaciation (A & B) in which changes have been interpreted as being original and indicating that there was a change in ocean pH during the recovery of the Snowball Earth. Data from the Clino core (C-I) show similar changes in the $\delta^{11}B$ and $\delta^{13}C$ values during a period where the oceans have not changed in pH. Obviously these $\delta^{11}B$ values from Clino have been diagenetically altered. From Stewart et al. (2015).

research is to constrain diagenetic signatures preserved within shallow water carbonate sediment records globally, demonstrating that many of these large magnitude shifts are diagenetic and are not associated with complex changes in long-term ocean chemistry.

PRELIMINARY RESULTS

The $\delta^{11}B$, $\delta^{34}S$, and clumped isotope values from Clino indicate regions of diagenesis resulting in isotopic excursions from accepted values of seawater, complementing XRD data showing recrystallization of aragonite to calcite in several regions throughout the core. In contrast, based on $\delta^{34}S$ values, Enewetak is dominated by an open system fluid flow.

Initial data indicates large magnitude shifts in $\delta^{11}B$ values are prevalent throughout the Clino core (Stewart et al., 2015) (Fig. 1), changes which may be related to pH variations associated with the degradation of organic material near or at the water table. The magnitude of these variations are similar to those measured in ancient sediments (Clarkson et al., 2015; Kasemann et al., 2010; Ohnemueller et al., 2014) which have been interpreted as being original and suggesting that there had been large changes in the pH of the oceans after major events such as the Permian-Triassic boundary and the end of the Marinoan glaciation. Future work will examine changes in the behavior of the $\delta^{11}B$ values associated with marine diagenesis.

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EVALUATING DRIVERS OF REEFAL TRANSITIONS OVER ~16MYR, ENEWETAK ATOLL

Colleen Brown, Megan Smith, Peter K. Swart, and Amanda M. Oehlert

PROJECT OBJECTIVES

- Examine trace element and stable isotopic composition of well-preserved corals and sediments from Pliocene and Miocene sections for comparison with the Modern.
- Quantify geochemical signatures including $\delta^{11}B$, B/Ca, Sr/Ca, P/Ca, U/Pb, $\delta^{13}C_{carb}$, $\delta^{18}O$, and various trace elements.
- Consider the timing and causes of transition from reefal boundstones to skeletal grainstones over the past ~16 Myr.

PROJECT RATIONALE

Over geologic time, the ecological framework of reefal environments has shifted from the first stromatolitic reefs to the Modern scleractinian coral-dominated reefs, with many variations in between. Drivers of ecological shifts have been attributed to major climatic changes, sea-level changes, and subsidence. To understand the environmental conditions that precipitate such ecological changes, the historical stress response of corals in the geologic record can provide key insight into the tempo and frequency of reefal transitions through time. Paleoseawater conditions have been shown to be recorded in coral skeletons and carbonate sediments, and geochemical proxies ($\delta^{11}B$, $\delta^{13}C_{carb}$, $\delta^{18}O$, B/Ca, Sr/Ca, P/Ca) can be useful in constraining changes in environmental conditions through time. The goal of this project is to reconstruct the paleoclimate and/or paleoceanographic changes that instigated reef decline, re-growth, and sedimentary facies shifts throughout the Enewetak KAR-1 core.

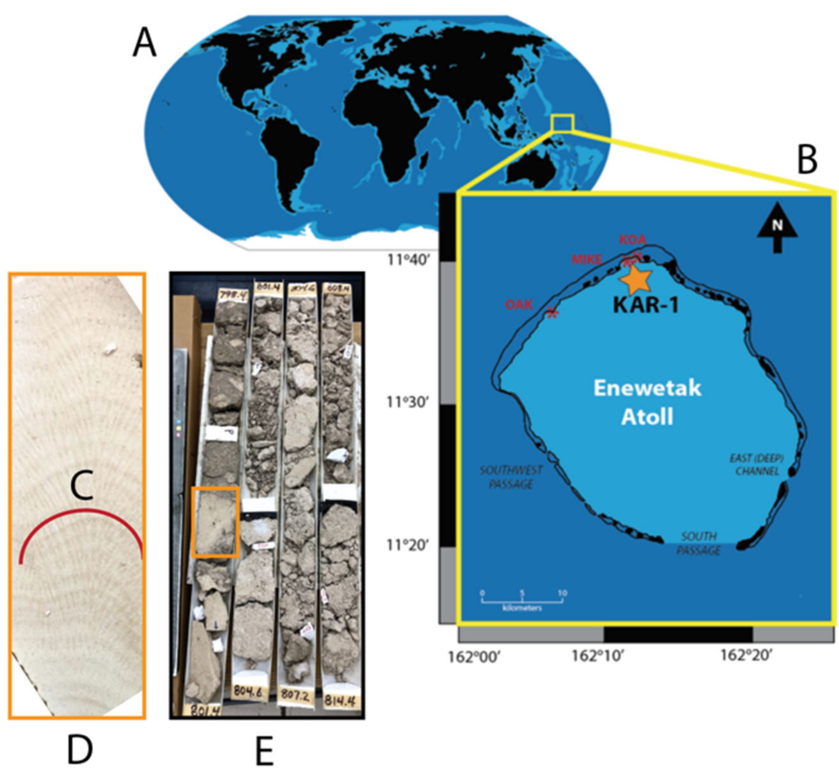

Figure 1. (A, B) Location map of KAR-1 in the Enewetak Atoll. (C) Growth band of (D) coral head. (E) KAR-1 sediment core

APPROACH

The KAR-1 core drilled into the Enewetak Atoll contains a sedimentary record with two sections that are proposed analogs for predicted 2030 and 2100 climate; the Mid-Pliocene warm period (~3.3-3.0 Ma; Burke et al., 2018), and the Miocene Climate Optimum (~17-14.7 Ma; Holbourn et al., 2015). KAR-1 was collected from Enewetak Atoll in the Marshall Islands, just outside the KOA crater that resulted from nuclear bomb testing in the late 1960s. More than 350 sediment samples and 35 coral skeleton slabs from the KAR-1 core (Fig. 1) will be analyzed in this study. Unaltered (>80% aragonite) fossil coral skeletons will be analyzed for stable isotopes ($\delta^{13}C_{carb}$ and $\delta^{18}O$ values) at the Stable Isotope Laboratory and the isotopic composition of boron, as well as elemental concentrations and ratios ($\delta^{11}B$, B/Ca, Sr/Ca, P/Ca, U/Pb), will be analyzed on the QQQ-ICP-MS. These coral based records will be compared to the same geochemical proxies analyzed in the bulk sediments. In particular, this study will focus on the transitions from reefal boundstones to skeletal grainstones. Coral extension rates and skeletal density will be analyzed for each coral head, and compared to the geochemically resolved conditions of paleoseawater to determine growth response to stress that may have precipitated an ecological shift. Proxies for climatic and oceanographic conditions in sediments across major transition zones between reefal boundstones and skeletal grainstones will be compared to determine climatic and oceanographic drivers for facies shifts.

SIGNIFICANCE

Reef growth on a geologic timescale has been suggested to be predominantly controlled by sea level, current configurations, and climatic fluctuations. In this study, we compare known sea-level oscillations and their sedimentary response (DNA, 1986) with new reconstructions of geochemical proxies for upwelling, sea surface temperature, and carbonate chemistry. Such environmental conditions are known to impact reef growth, as corals are restricted to environments with narrow ranges in temperature for optimal growth (26-28°C; Hubbard, 2015). In concert, these analyses will enable an evaluation of the relative importance of varying sea surface temperature, sea-level oscillations, and oceanographic conditions on reef development and facies shifts in a tropical atoll environment over the past 16 Mys.

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APPLICATION OF THE Δ_{48} PROXY TO THE REAL WORLD

Peter K. Swart and Chaojin Lu

OBJECTIVE

The goal of this project is to apply the newly calibrated Δ_{48} proxy to (i) issues of non-equilibrium precipitation of carbonates, and (ii) the geothermal resetting of the Δ_{48} proxy during heating.

KEY POINTS AND PROJECT DESCRIPTION

We have established a calibration between the Δ_{48} values of carbonates precipitated at nine temperatures (5 to 73°C) and reacted at 90°C in a common acid bath. With this equation we will investigate the Δ_{48} values in a number of systems which exhibit non-equilibrium precipitation behavior as regards their Δ_{47} values. In addition, we will investigate how the Δ_{48} value compares with the Δ_{47} values during solid-state transformation.

PRELIMINARY RESULTS

We have established an empirical equation between temperature and the Δ_{48} value (Fig. 1) of carbonate precipitated in the laboratory. This equation is consistent with the theoretical relationship (Hill et al., 2014; Wang et al., 2004). Based on the theoretical work of Guo (2020) it may be possible to combine both the Δ_{47} and Δ_{48} values and therefore derive the true temperature of precipitation, even in situations in which the clumped isotope values are known to have precipitated in disequilibrium. For example, Figure 2 shows measurements from a coral in which the Δ_{47} values are known to give temperatures which are too cold. In contrast the Δ_{48} values produce temperatures which are too warm. Based on the work of Guo (2020) this pattern is completely predictable and can be used to extract the correct temperature of precipitation. Similar results, but in the opposite sense, (Δ_{47} is too low and the Δ_{48} is too high) can be obtained from cave deposits.

A second objective of this work will be to compare the behavior of the Δ_{48} and Δ_{47} value during heating. Preliminary work suggests

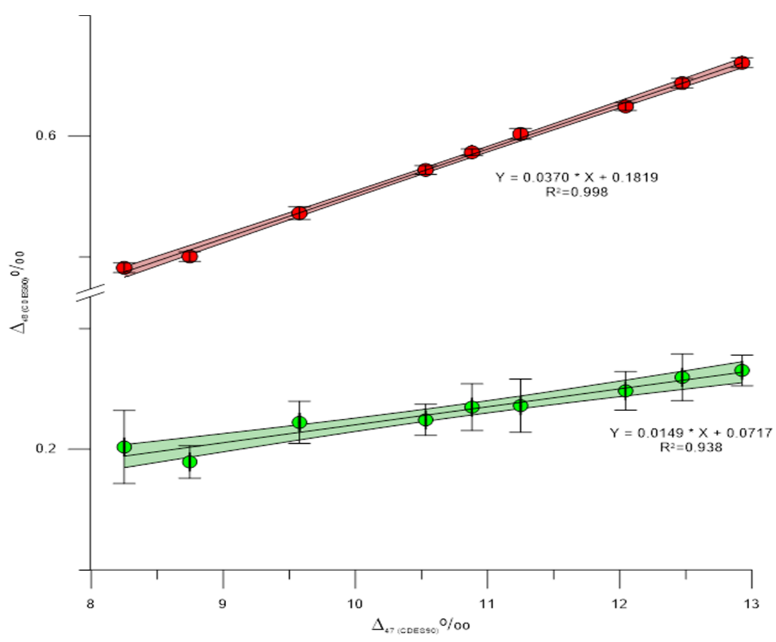

Fig. 1: Calibration between the Δ_{48} values and temperature ($10^6/T^2$) for the PBL1 method. Also shown is the calibration between Δ_{47} values and temperature measured during the same analytical sessions. Larger error bars on the 50 and 72°C samples reflect a lower number of replicates measured on these samples.

that the Δ_{48} value may be more susceptible to resetting than the Δ_{47} value and therefore may be useful in examining burial history in cases where the material has only been shallowly buried.

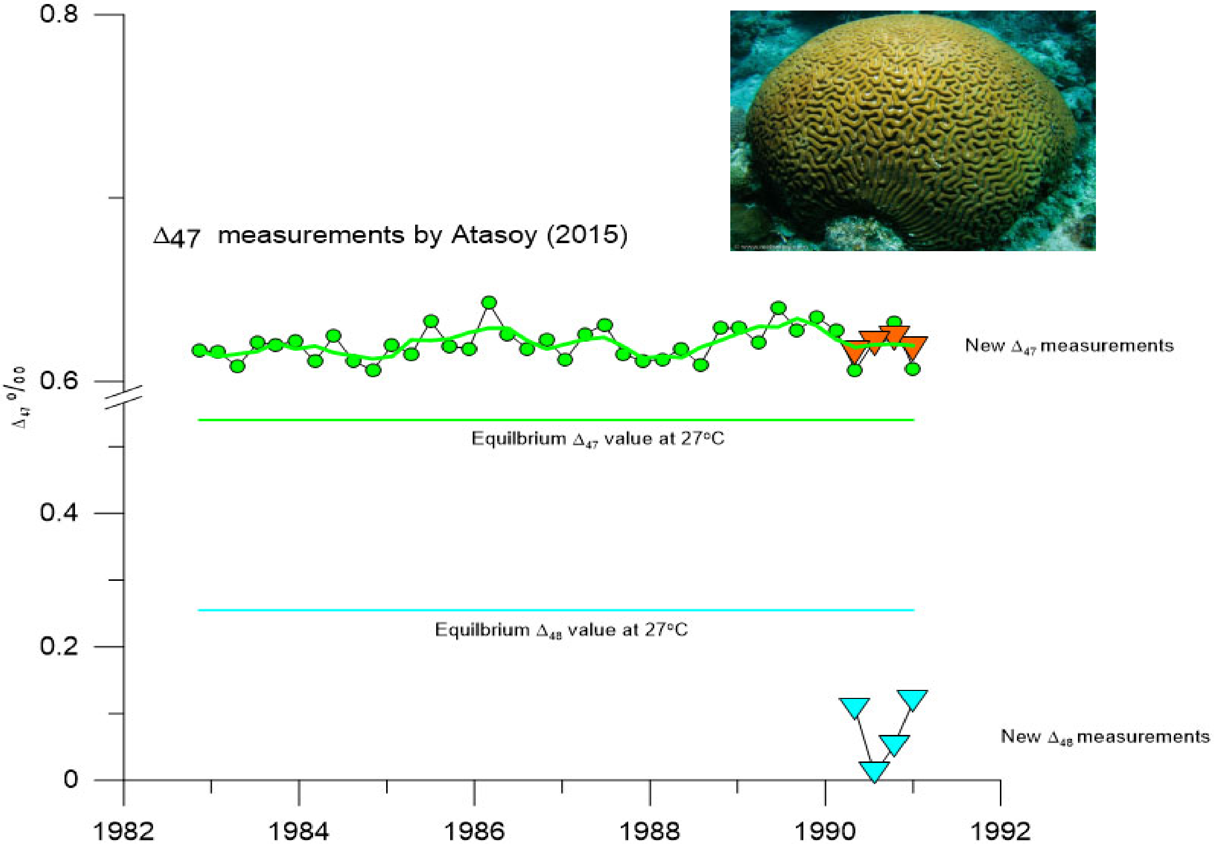

Fig. 2: Δ_{47} values (green) measured in coral collected from Tobago (Atasoy, 2015) and samples from the same coral (orange symbols) measured at the same time as the Δ_{48} measurements blue symbols. Equilibrium lines (blue and green) are based on the calibration shown in Fig. 1 for Δ_{48} and from Swart et al. (2019) for Δ_{47}.

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EARLY MARINE CEMENTATION PROCESSES AND VELOCITY EVOLUTION

Mara R. Diaz, Ralf J. Weger, Peter K. Swart, and Gregor P. Eberli

PROJECT OBJECTIVES

- To investigate the role of microbes in ooid lithification processes that leads to the formation of grapestones and rocks.
- Compare the influence of biologically mediated versus inorganic precipitated cements on acoustic velocity and rock strength of carbonates.

PROJECT RATIONALE

Diagenetic alterations can trigger drastic changes in the petrophysical properties of carbonate grains. Newly formed cements can occlude or partially line pores which results in changes in the strength of granular rocks. When the new precipitates form at grain-to-grain contacts, an increase in stiffness and shear stress behavior is often foreseeable, affecting compaction, bulk and shear modulus (Bernabe et al. 1992; Dvorkin and Nur, 1996). The induction period for inorganic carbonate crystal precipitation at grain contact and non-contact areas – based on *in vitro* experiments with supersaturated solutions of $CaCO_3$ – can occur in as little as a few weeks (Fig. 1), while in the marine-realm, cementation processes can take place on a scale of a few months or years.

There is increasing evidence to suggest that cementation is not a purely abiotic process as organomineralization processes – mediated by microbes and EPS biofilms – can induce many forms of early cements, including micrite envelopes, micritic

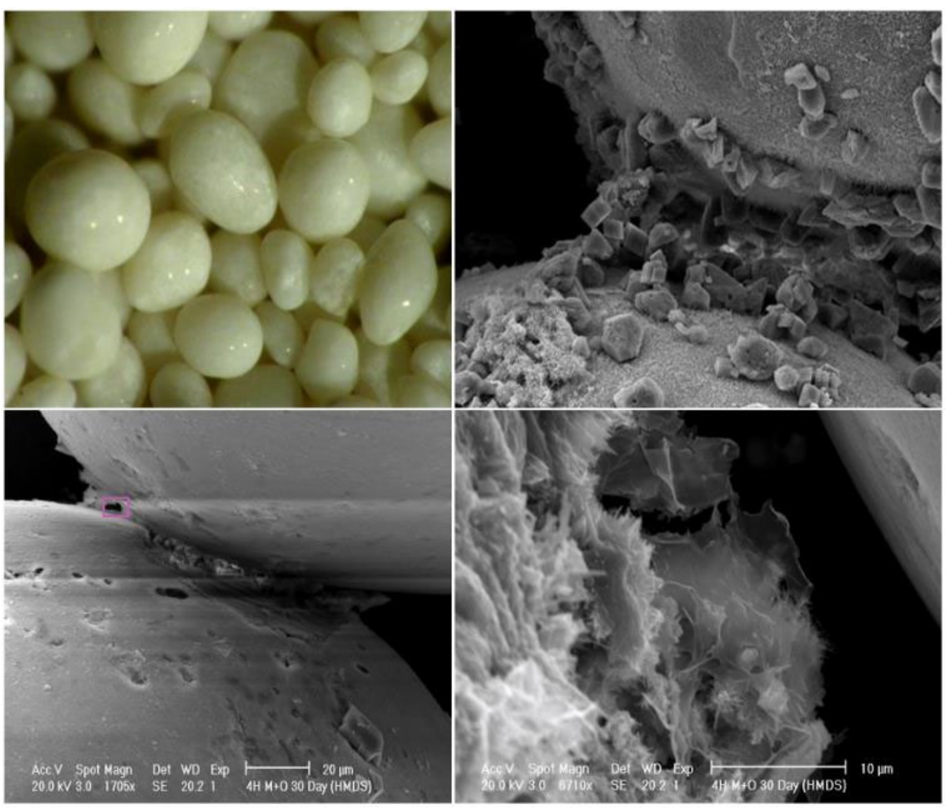

Figure 1: Results of inorganic and microbially mediated precipitation study. Top right, clean ooids before experiment. Top right, calcium carbonate crystals precipitated during the experiment. Precipitation occurs preferentially at the ooid-to-ooid grain contacts. Bottom right, illustration of microbially induced cementation after 30 days. Note the EPS at grain contact area.

bridges, meniscus cements and fringing cements. This evidence strengthens the notion that microbes are important in the initial cementation and stabilization of sediments. The latter is further supported by our previous observations on a myriad of interclast marine samples from the Bahamas and Hamelin Pool, Australia and in-house experiments with in-vitro incubations of loose ooid sands in the presence and absence of native microbial populations. Under the presence of microbial flora, our experiments show that the initial stages of grain consolidation can occur at 30 days with more advanced stages at 60 days. In contrast, sterilized ooids remain unconsolidated after 60 days (Fig. 1).

Based on the growing evidence supporting the influence of microbes in cementation, this study addresses their role and their impact on the elastic properties following grain cementation and rock formation. Of special interest is determining whether microbial cementation enhances the stiffness of loose sands and how it influences velocity and compaction. To this end, experiments that quantify both the chemical changes in the fluids and the diagenetic and petrophysical changes within the sediments (i.e. acoustic velocity and permeability) will be undertaken in parallel with SEM observations.

APPROACH

To determine the extent to which microbial precipitation affects rock-physics, experiments will be tailored to:

Quantify the geochemical alterations in the fluids and petrophysical changes as unconsolidated ooid sands undergo compaction through time. To assess differences in petrophysical properties and the effect of microbial colonization on lithification, two sets of incubations - representing abiotic and biologically mediated precipitation - will be undertaken in chambers containing ooids that have undergone physical and chemical sterilization (to ensure axenic or microbial free conditions), whereas microbially mediated precipitation will use freshly collected ooids with their native microbial flora. Visual inspection of grain contact areas will use petrographic thin sections and SEM-EDS analyses to identify mineral structure composition, grain binding, porosity and microbial colonization. The involvement of extracellular polymeric substances (EPS) and the presence of ACC as a precursor to cementation processes will use SEM analysis.

KEY DELIVERABLES

A data set will be created capturing changes in acoustic velocity and fluid flow permeability generated by microbially and non-microbially induced precipitation. High-resolution images using SEM will provide insights on the role of microbes and associated EPS in precipitated material and their preferential location within the rock framework.

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SEARCHING FOR ELEMENTAL SIGNATURES OF SWEET SPOTS IN THE VACA MUERTA FORMATION

Amanda M. Oehlert, Ralf J. Weger, Gregor P. Eberli and Laura Rueda

PROJECT OBJECTIVES

- Conduct high resolution elemental analysis on ~400 samples collected from short cores drilled into outcrops of the Vaca Muerta Formation.
- Apply the increased analytical sensitivity (ppt to ppq) and elemental range of QQQ-ICP-MS to search for diagnostic elemental signatures of high TOC 'sweet spots'.
- Statistical analysis of elemental composition (rolling window regression, principal component analysis, pairwise correlations).
- Synthesize with previously collected data (Aavatech XRF Core Scanner and TerraSpec Halo Mineral Identifier) for integrated geochemical perspective on the Vaca Muerta Formation.

PROJECT RATIONALE

Detailed, multi-scale geomechanical, sedimentological, and diagenetic studies of the Tithonian to Valanginian Vaca Muerta Formation have demonstrated the spatial variability of this source rock, and the important role it plays in the Neuquén Basin petroleum system in Argentina (Eberli et al., 2017; Sánchez et al., 2018). Sweet spots, or intervals containing high total organic carbon (TOC), have been found to

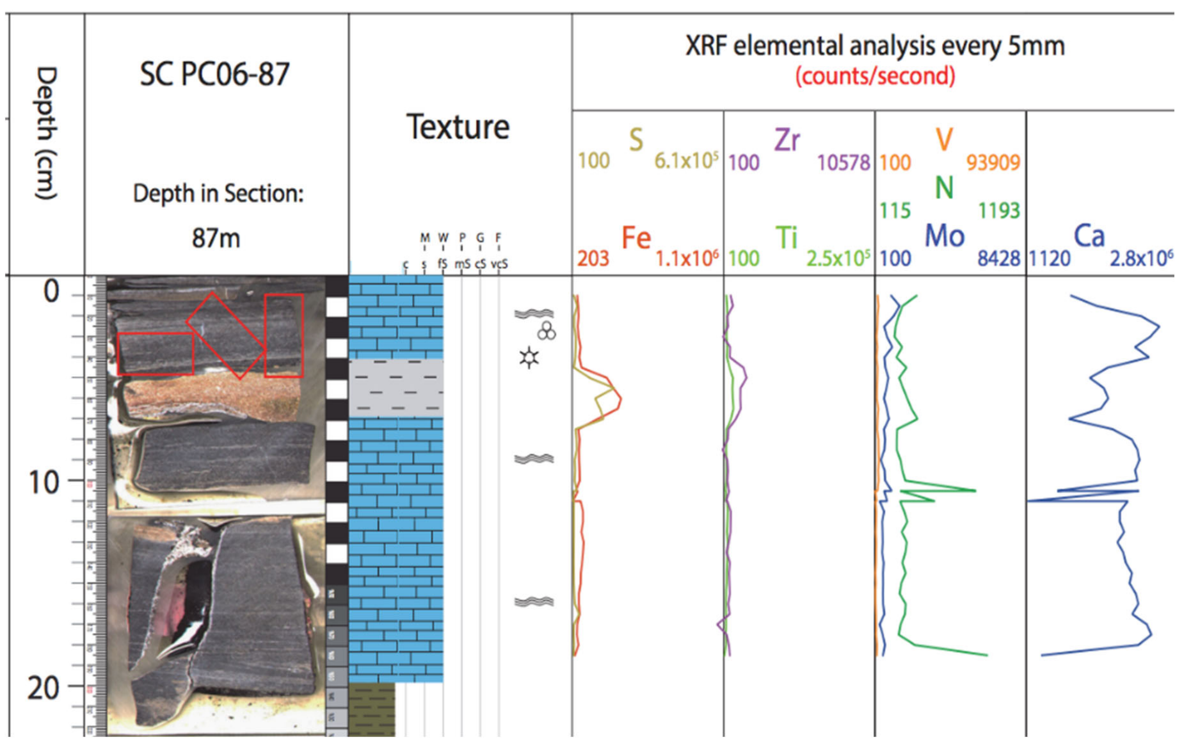

Figure 1. Example of a short core from Puerta Curaco, the lithological description, and results of XRF core scanning conducted by the Vaca Muerta Team at the CSL-Center for Carbonate Research (Eberli et al., 2017).

occur in not readily predictable patterns within the progradational system in both the subsurface and outcrop (Eberli et al., 2017). Recent geochemical analysis of the Vaca Muerta Formation and other globally distributed unconventional reservoirs documented heterogeneity within these depositional environments that is related to facies transitions, mineralogy, and redox state (Sánchez et al., 2018). The development of new analytical techniques like triple-quadrupole inductively coupled plasma mass spectrometry (QQQ-ICP-MS) expands the elemental analytes of interest from ~20 to more than 50 elements, and significantly enhances the analytical resolution of such analyses to the parts-per-trillion to quadrillion threshold. We will conduct discrete analyses of quantitative elemental concentration of ~70 elements using QQQ-ICP-MS to search for diagnostic elemental signatures of sweet spots in the Vaca Muerta Formation.

APPROACH

Approximately 400 discrete samples will be collected from the suite of short cores drilled in the Puerta Curaco outcrop area of the Vaca Muerta Formation. Quantitative elemental analysis will be conducted using a newly acquired Agilent 8900 QQQ-ICP-MS, which provides chemical resolution of isobaric interferences, the lowest detection limits for notoriously difficult to measure elements like sulfur, silicon, phosphorus and arsenic, and the possibility to measure isotopic composition of some elements. Statistical analyses (rolling window regression, principal component analysis, and pairwise correlations) will be conducted to quantitatively evaluate elemental signatures and their relationship to TOC data.

SIGNIFICANCE

Enhanced elemental characterization of samples of short cores from the Vaca Muerta Formation at the Puerta Curaco section are expected to provide new insight into geochemical indicators of high TOC intervals (sweet spots) and contribute to the understanding of the geological processes that produce spatial heterogeneity in elemental concentrations. Integration of QQQ-ICP-MS data and statistical analyses with previously collected elemental (XRF Core Scanner) and mineralogical data with a handheld Near-Infrared Spectrometer will provide a high-quality quantitative calibration of field-based measurements of the Vaca Muerta Formation.

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DECODING SUBTLE DIAGENETIC ALTERATION: COMBINING GEOCHEMICAL AND PETROPHYSICAL APPROACHES

Amanda M. Oehlert, Peter K. Swart, Ralf J. Weger, and Gregor P. Eberli

PROJECT OBJECTIVES

- Contribute enhanced records of $\delta^{13}C$ and $\delta^{18}O$ values, as well as major, trace, and ultra-trace elemental concentrations at Unda, Clino, ODP Site 1003, and ODP Site 1006.
- Assess diagenetic variability (cementation/dissolution, isotopic signatures) in shallow marine carbonates using geochemical, petrophysical, and seismic sequence stratigraphic approaches.

PROJECT RATIONALE

Diagenetic alteration in shallow marine carbonates is often complicated by varying degrees of cementation, dissolution, and recrystallization in a range of diagenetic regimes through space and time. Recently, the utility of integrating sedimentology, geochemistry, and petrophysical logs has provided a high-resolution perspective into both cryptic and obvious diagenetic alteration in the Clino core from Great Bahama Bank. This multi-disciplinary approach incorporated a statistical analysis of carbonate $\delta^{13}C$ and $\delta^{18}O$ values using rolling window regression (RWR, Oehlert and Swart, 2019) with the velocity-deviation log ("DL", Anselmetti and Eberli, 1999) to produce a high-resolution perspective of the changes in cementation and diagenetic signatures within the core. In some instances, this analysis identified significant deviations in the DL without a corollary signature in the carbonate $\delta^{13}C$ and $\delta^{18}O$ values or RWR, suggesting either a zone of dissolution, or a zone of rock-buffered diagenesis depending on the sign of the deviation in the DL. Such ambiguities require further analysis to identify unique combinations of geochemical and petrophysical signatures for major diagenetic processes in shallow marine carbonates.

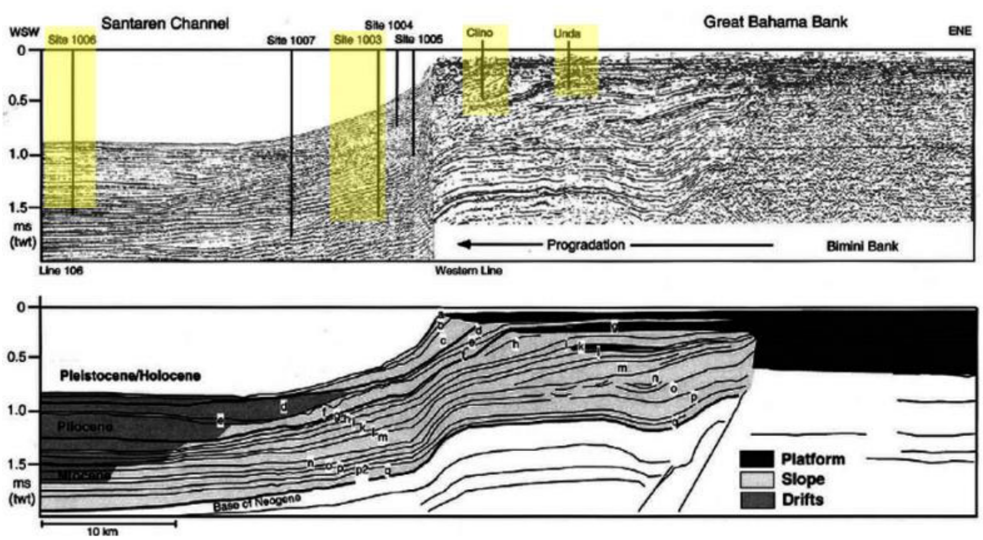

Figure 1. Seismic cross section across the western margin of Great Bahama bank. Yellow boxes indicate locations of Clino, Unda, ODP Sites 1003 and 1006, which will be analyzed in this study (after Eberli, 2000).

APPROACH

To improve permeability estimates from the DL, we will integrate the resistivity log into our multi-disciplinary analysis. DL inherently focuses on differences in the rock framework (e.g., fast rocks with simple geometry vs. slow rocks with complex geometry). Incorporating resistivity logs will allow us to focus also on variations in pore connectivity. Resistivity decreases with the number of pore connections and will allow us to distinguish between connected and separate vug porosity (Verwer et al., 2011). Combining velocity and resistivity logs will thus help discriminate stratigraphic horizons with cemented pore space, resulting in fast velocity and high resistivity intervals from horizons with interparticle velocity that display high velocity but low resistivity.

To develop a more nuanced perspective into the diagenetic impacts of repeated Neogene sea-level oscillations, we will expand our dataset to include a proximal-distal transect (Fig. 1) of shallow marine depositional environments. Incorporation of cores Unda and Clino on top of Great Bahama Bank (Ginsburg, 2001) with cores at ODP Sites 1003 and 1006 on the lower slope and basin, respectively, will refine our understanding of the spatial heterogeneity of the diagenetic overprint from the shallow to the deep marine environment regarding both cementation/dissolution and geochemical signatures. We will contribute additional measurements of $\delta^{13}C$ and $\delta^{18}O$ values, and new measurements of major, trace, and ultra-trace elemental concentrations using ICP-QQQ in these cores coupled with detailed RWR and DL analyses. Finally, these observations will be integrated into a transect-wide assessment of diagenetic alteration through the incorporation of sequence stratigraphic framework at the seismic scale.

SIGNIFICANCE

Incorporation of petrophysical and geochemical approaches in the characterization of diagenetic impacts on shallow-deep marine carbonates has revealed zones of subtle alteration that were previously "below detection". Integration of RWR, DL, with the resistivity log and elemental concentrations, and seismic sequence stratigraphy is expected to provide new insights into the influence of repeated diagenetic alteration over the past 10 Mys.

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DETECTING PORE TYPES USING VELOCITY AND RESISTIVITY

Ralf J. Weger and Gregor P. Eberli

PROJECT OBJECTIVES

- Discriminate connected interparticle from separated moldic porosity using petrophysical properties.
- Combine resistivity and velocity to discriminate samples with simple pore geometries and connected pores from samples with simple pore geometries and disconnected pores.

PROJECT RATIONALE

Carbonates with high porosity can yield high velocity if they contain a stiff frame that allows the acoustic wave to travel with high speed. These high-velocity, high-porosity rocks can have either interparticle or separated moldic porosity, reflecting the contrasting stiffening process. In fast rocks with interparticle pore space the stiff frame is produced by cementation of grain-grain contacts while in separated moldic rocks the frame is basically the completely cemented pore space. Both processes result in high velocity but because of the pore type the permeability is different. Moldic rocks have low permeability while high velocity rocks with interparticle pore type have a high permeability (Fig. 1).

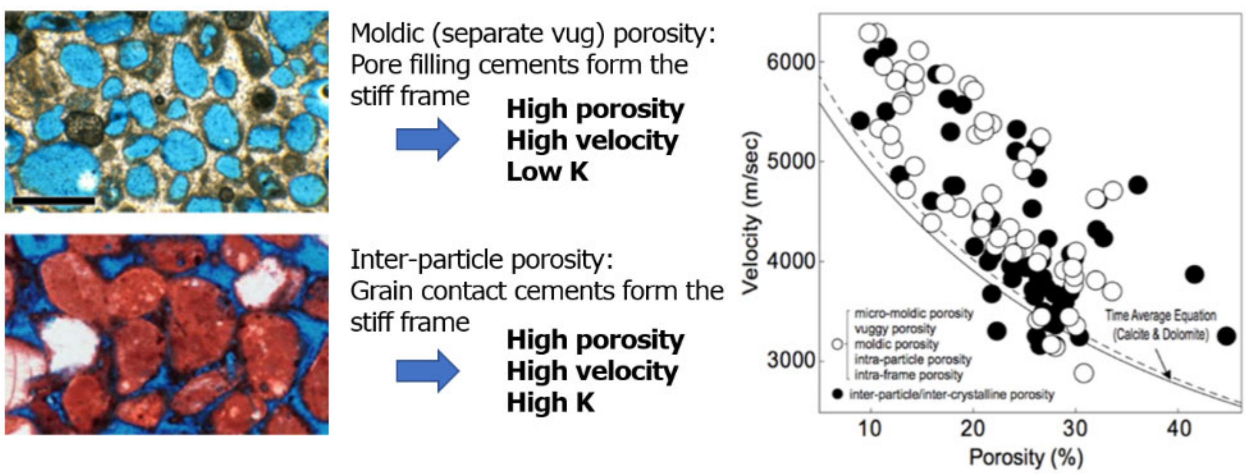

Figure 1: Left: Illustration of the two pore types and their petrophysical characteristics. Right: Velocity-porosity plot of carbonates separated into interparticle/intercrystalline and different types of separate vug porosity. Both can have very high velocity at any given porosity (from Weger et al., 2009).

It is difficult to distinguish between these two pore types using Digital Image Analysis (DIA) because both yield large, simple pores (Weger et al., 2009). Resistivity also relates to pore type but is also strongly dependent on pore connectivity and the number of pores (Verwer et al., 2011; Norbisrath et al., 2015). As a result, resistivity is lower when the pores are more connected in contrast to separated pore networks that usually show higher resistivity measurements (Fig. 2). This project tests how accurately these two pore types can be distinguished using laboratory measurements of acoustic velocity and electrical resistivity (Fig. 2).

APPROACH

Compare samples with simple internal pore geometry that are either connected (high K), or isolated (low K) to evaluate and quantify how resistivity will discriminate connected from unconnected simple pore networks.

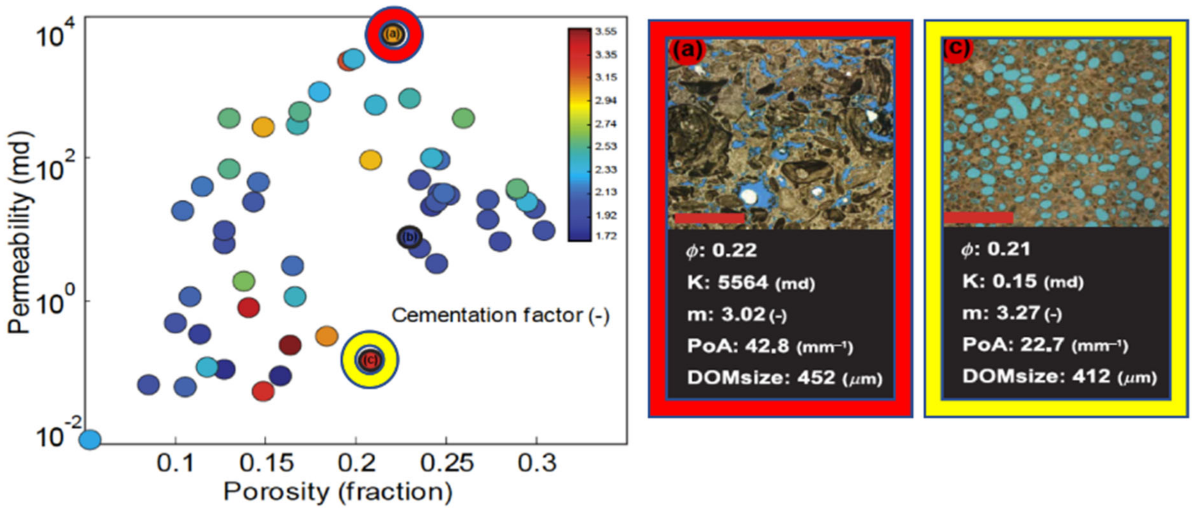

Figure 2: Permeability-porosity cross plot showing resistivity derived cementation factor (m) superimposed in color. High velocity samples with similarly simple pore networks and DIA parameters (a and c) show subtle differences in resistivity.

WORKPLAN

The CSL has measured several hundred samples for velocity, resistivity, porosity, permeability and related their values to quantitative pore geometry parameters determined using DIA. We plan to mine this data base for samples of similarly high velocity and simple and large pores, as documented by the DIA parameters of low perimeter over area (PoA) and high dominant pore size (DomSize), and then assess the resistivity differences in these samples. It is expected that the velocity in each sample is relatively high while the resistivity will be "high" in samples with separate vug porosity and "low" in samples with interparticle porosity. Samples that do not follow this expected trend will be further examined to determine the cause of the indiscriminate behavior.

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Characterization of The Agrio Formation, Neuquén Basin, Argentina

Ralf J. Weger, Peter K. Swart, and Gregor P. Eberli

Project Objectives

- Characterize the facies, TOC distribution, geochemical signature and petrophysical properties of the Agrio Formation in the Neuquén Basin.
- Compare these data with the existing data set in the Vaca Muerta Formation to assess similarities and differences in these two marine stages of the basin following terrestrial conditions.

Project Rationale

During the late Jurassic and early Cretaceous, the Neuquén Basin in Argentina experienced three similar sedimentary cycles of continental to marine successions (Fig. 1). In the Tithonian, terrestrial and lacustrine environments were rapidly inundated by marine waters, forming a basin that was subsequently filled with organic-rich clinoforms of the Vaca Muerta Formation. Following a relative sea-level fall in the early Valanginian, sedimentation was limited to the central part of the Neuquén Basin, with the deposition of a predominantly clastic, continental to shallow marine wedge (Schwarz et al., 2006). Renewed flooding in early Late Valanginian, re-established marine conditions and resulted in deposition of the organic-rich mudstones of the Pilmatué Member of the Agrio Formation. Another dramatic sea-level fall resulted in terrestrial and aeolian conditions over most of the Neuquén Basin before a third flooding re-established marine conditions and deposition of the Agua de la Mula Member of the Agrio Formation (Fig. 1).

After each marine flooding event organic-rich strata was deposited. The Vaca Muerta Formation is more enriched in TOC than the younger Agrio Formation with the latter containing 2-5% TOC in a 50-400 m thick section (Legarreta and Villar, 2011). The facies associated with each formation, however,

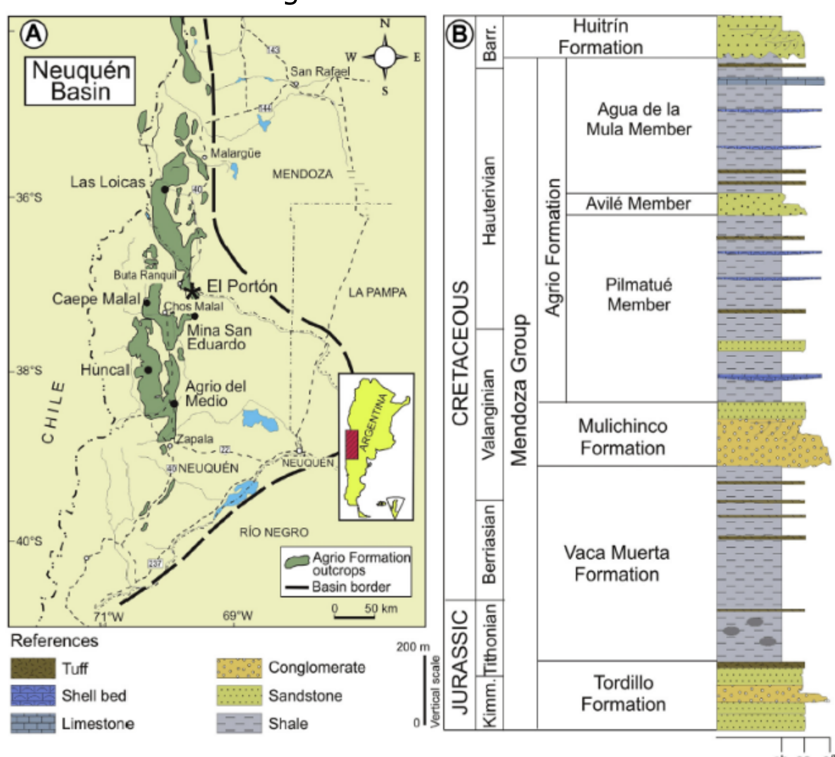

Figure 1: Location of Agrio Formation outcrops (A) and stratigraphic column of the Medoza Group (B) (Aguirre-Urreta et al., 2017)

vary, indicating that the sedimentary system changed slightly. To capture the variability and similarities between formations we plan to characterize the Agrio Formation as we did with the Vaca Muerta Formation i.e., with detailed lithologic sections that are accompanied by geochemical sample analysis and gamma ray measurements every meter. Subsequently, these two data sets are compared to quantitatively assess the differences.

APPROACH

In the areas of Puerta Curaco, Aguada de los Tamariscos, Yesera del Tromen, and Pampa Tril we measured over 20 different sections of the Vaca Muerta Formation with a total length of over 2000 m, covering the stratigraphic column from the Tordillo, through the Quintuco up to the Mulichinco Formation to characterize facies and geochemical signatures. The Mulichinco Formation separates the Vaca Muerta Formation from the overlying Agrio Formation. We plan to measure through the Mulichinco Formation with low sampling rates (5 m spacing) to provide a representation of this interval, but then continue with 1 m spacing in the Agrio Formation. At the Puerta Curaco location, only the lower portion of the Pilmatue Member (Fig. 1) is well exposed, but a high-resolution lithologic log, spectral gamma ray, and geochemical samples every meter will provide the basis for correlation to other, better exposed outcrop locations of the Agrio Formation. Some scouting will be required, but well exposed outcrops of the Agrio Formation have been documented by several authors (Uliana and Legarreta 1993; Aguirre-Urreta et al., 2017; 2019).

SIGNIFICANCE

These new lithologic sections and analyses will provide the required high-resolution data necessary to characterize the Agrio Formation for comparison with the Vaca Muerta Formation. These observed differences and similarities between the two formations will aid in assessing the potential of the Agrio Formation.

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VIRTUAL FIELD TRIP TO THE VACA MUERTA FORMATION, ARGENTINA

Ralf J. Weger, Arthur C.R. Gleason, and Gregor P. Eberli

PROJECT OBJECTIVES

- Provide the opportunity to visit the outcrops of the Vaca Muerta Formation in the Puerta Curaco area in the form of an "Interactive Multiuser Virtual Reality" field trip.
- Explore georeferenced content such as measured lithologic sections, short cores, detailed photographs in the context of their realistic location within a textured high-resolution 3D digital elevation model (DEM).

PROJECT RATIONALE

Communicating geologic findings or teaching basic geologic concepts requires integrative communication in the field in addition to merely reporting results in a paper. COVID-19 restrictions on travel have made it difficult to impossible to perform field geology and/or provide opportunities to visit outcrops during geologic field trips. Virtual reality (VR) fieldtrips can partly replace the outcrop-based knowledge transfer. To provide the 3D information available at outcrop, a virtual environment needs to be in 3D and integrated with supplemental data.

APPROACH

We will use drone images collected from the Puerta Curaco outcrops using a small, unmanned aircraft system (sUAS, or drone) to construct a high-resolution 3D digital elevation model (DEM). The models will be populated with georeferenced supplemental information, including measured lithologic sections, measured

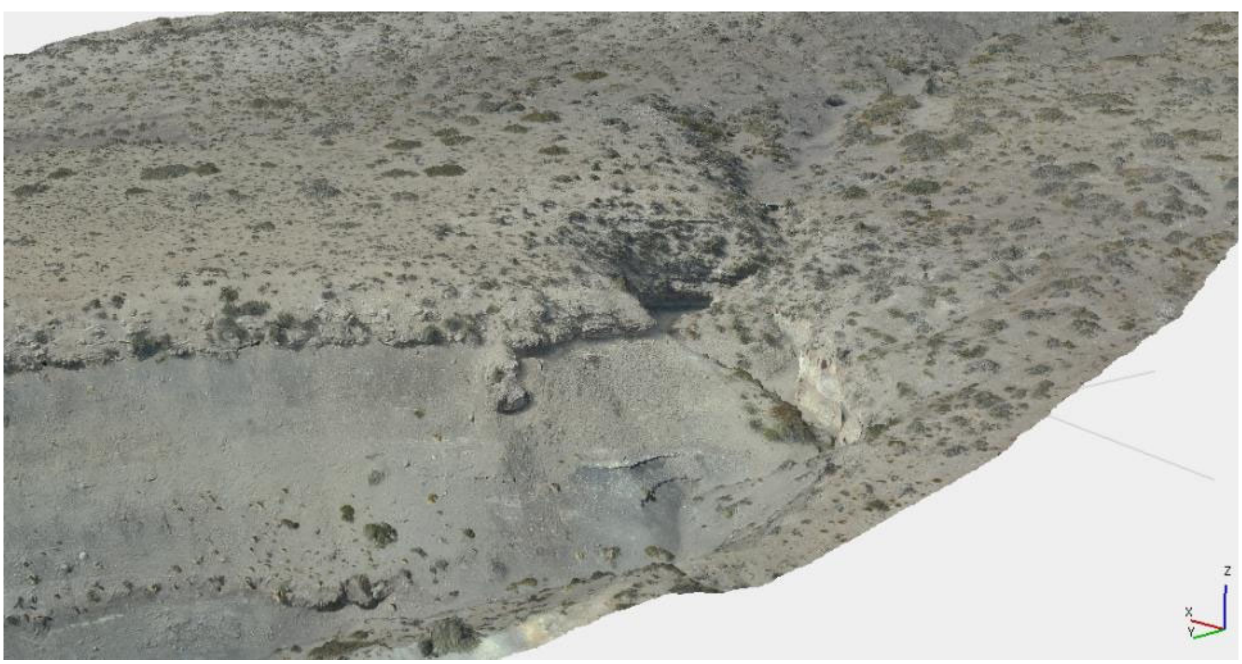

Figure 1: Drone image-based 3D Model of outcrop at Puerta Curaco.

geochemical data, detailed photographs, core descriptions, core photographs, and photomicrographs. We explore the software package of 3D Gaya (imagedreality.com) as the virtual environment that enables the integration of outcrops and supplemental data into a photorealistic environment. This platform provides virtual 3D views that can illustrate dimensions, textures, and lateral connectivity not possible in regular 2D presentations.

GOAL AND SIGNIFICANCE

This approach will facilitate knowledge transfer and enable participants to perform their own analysis and extract information from the models within the VR environment. They will be able to measure and trace features and share their interpretations in real time with others in the virtual environment.

Although virtual reality field trips will never be an alternative to real field work, they provide an integrated learning environment that can serve as an alternative to real field trips while travel is difficult or impossible. In addition, this technique can be incorporated in short courses to provide a 3D illustration of learning points in the classroom environment.

ENHANCED OUTCROP TO SUBSURFACE CORRELATION IN THE VACA MUERTA FORMATION

Taury Smith[1], Ralf J. Weger, and Gregor P. Eberli
[1] *Smith Stratigraphic LLC*

PROJECT OBJECTIVES

- Tie the outcrop to the subsurface based on the composition determined from thin sections and cuttings from 20 wells and outcrop sections across the basin.
- Evaluate compositional similarities and differences in the sequences and cycles to capture the lateral and vertical facies variability within the Vaca Muerta Formation.
- Provide a (semi)quantitative comparison of facies similarities in the outcrop and subsurface.

PROJECT RATIONALE

In the past we have successfully correlated the outcrop successions of the Vaca Muerta Formation in the Neuquén Basin to the subsurface with geophysical and geochemical data. Synthetic seismic sections constructed from facies and geometries observed in the Picun Leufu area and the Sierra de la Vaca Muerta (SdlVM) are very similar to the geometries observed on seismic sections (Zeller et al.,2015 a, b). The correlation of outcrop sections to core and well logs is achieved by adding spectral gamma ray, TOC and other geochemical properties with high resolution (0.5-1m spacing) to the lithology in each section. Key log-signature subdivisions from the subsurface correspond to sequence stratigraphic divisions identified in the outcrop sections (Eberli et al., 2017).

With these correlations in hand an enhanced correlation is possible that considers facies variations within the cycles and sequences. This correlation is based on a quantitative analysis of thin sections from outcrop successions and its comparison to the subsurface data (Fig. 1). The advantage of this facies-based correlation is that it captures the sedimentologic variations created by the cyclic deposition. In addition, it reflects the proximal distal facies changes as well as the changes through time.

APPROACH

The study can rely on a large data set from the subsurface that Taury Smith has produced and which will be compared to the outcrop sections. The data set consists of a cuttings and core study of more than 20 wells across the basin from the top of the Quintuco to the base of the Vaca Muerta using more than 5000 thin sections. Based on the cuttings and logs, detailed stratigraphic columns are constructed that allow sequences and cycles to be picked (Fig. 1). Taury Smith will work with us to assemble a similar data set in our outcrop sections so that they can be compared to the subsurface. Some of the wells he studied are within 10 km of the outcrop belt.

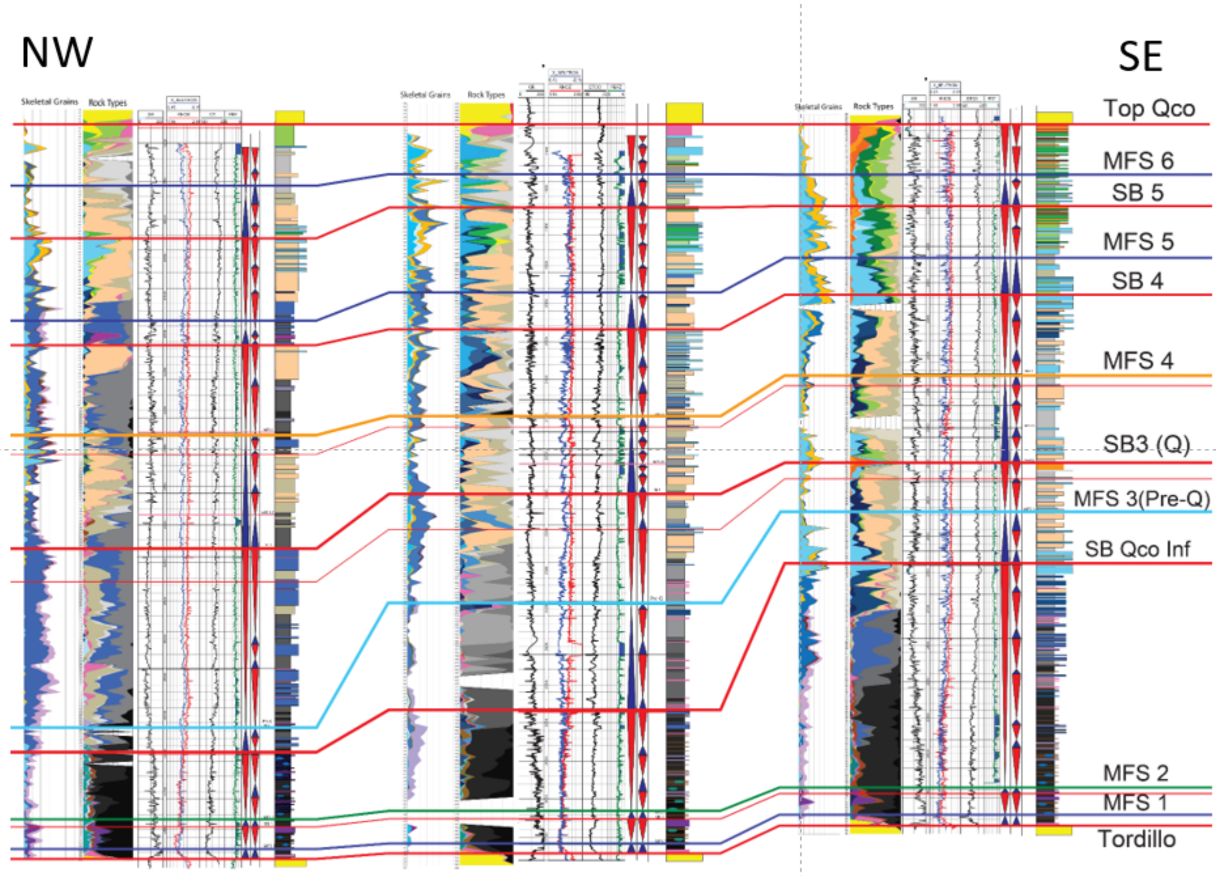

Figure 1: Correlation of cycles and sequences between three wells using cuttings and cores together with log information. The quantification of the composition adds valuable information about the lateral and vertical changes of facies.

SIGNIFICANCE

This facies-based correlation of outcrop to subsurface will add valuable information regarding the facies changes between the outcrop at the western side of the basin and subsurface areas further to the east. If the comparison reveals strong similarities, it will strengthen the potential of the outcrops to act as analogs for the subsurface. Variations would indicate lateral facies changes along the clinoforms in the basin.

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