CSL
Center for Carbonate Research
and Education

Prospectus
2020

UNIVERSITY OF MIAMI
ROSENSTIEL
SCHOOL of MARINE &
ATMOSPHERIC SCIENCE

CSL
CENTER FOR CARBONATE RESEARCH

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Geobiology and Geochemistry

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
Mark Grasmueck	Adjunct Professor, Subsurface Imaging
Paul (Mitch) Harris	Adjunct Professor, Applied Sedimentology
James S. Klaus	Associate Professor, Paleontology
Donald F. McNeill	Scientist, Sedimentology, Stratigraphy
Sam Purkis	Professor, Sedimentology/Remote Sensing
Peter K. Swart	Professor, Geochemistry
Amanda Oehlert	Assistant Professor, Geochemistry

SCIENTISTS

Mara R. Diaz	Geo-Microbiology
Ralf J. Weger	Petrophysics

ASSOCIATE SCIENTISTS

Greta Mackenzie	Diagenesis/Petrography

SCIENTIFIC COLLABORATORS

G. Michael Grammer	Oklahoma State University
Christian Betzler, Thomas Lüdmann	University of Hamburg, Germany
Dierk Hebbeln and colleagues	University of Bremen, Germany

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Sara Bashah, Colleen Brown, Emma Giddens, Anna H. Ling, Cecilia Lopez-Gamundi, Evan Moore, Megan Smith, Lisa Tanh, Mingyue Wu

RESEARCH ASSOCIATE

Amel Saied

STAFF

Karen Neher	Manager, Business Operations

2020 RESEARCH FOCUS

The three main research directions in Modern and Ancient Carbonate Systems are mainly focused around sediment production and distribution, in particular establishing the respective role of physical, chemical, and biological processes in carbonate mud production on Great Bahama Bank. The second focus is modern and ancient carbonate contourite deposits. The third direction is to investigate the Yucatan Platform and compare its evolution to the platforms of the Bahamian archipelago.

Results from ongoing research on the origin of non-skeletal mud production in whitings on Great Bahama Bank reveal seasonal variations in the frequency of whitings, indicating that changes in temperature or hydrodynamics during winter and summer months might partly control the precipitation. To further study this variability and the underlying causes, two new approaches are planned. The first is to use a newly developed Convolutional Neural Network (CNN) on MODIS imagery from Great Bahama Bank to quantify the whiting occurrences accurately through time. Systematic chemical analysis of the water masses within whiting hot-spot areas will provide critical data needed for the creation of numerical models of saturation state in the water masses hosting the production of these whiting events. A large-scale platform wide sediment budget analysis and distribution will assess the influence of hydrodynamics on sedimentary facies and off-platform sediment transport. A study of the migration of facies belts complements this effort.

In the off-bank carbonate environment, the focus is on understanding current deposits in carbonates. Four projects investigate various aspects of carbonate contourite drifts. The first is a compilation of modern and ancient carbonate drift systems to provide a comprehensive overview of the different types, dimensions and sedimentary characteristics. This information will help to: a) develop models of current-controlled erosion and deposition in carbonates in slope and basinal settings and b) evaluate the carbonate drift systems with regard to their reservoir and seal capacity. Of special interest are coarse-grained channel-related drift deposits that form delta-like sedimentary bodies. A combined sedimentologic and geophysical study of such a delta drift in the Maiella mountains in Italy will test the hypothesis that the formation of these drift deposits are the combined product of hyperpycnal flow - originating from the semi-continuous current flowing through the feeder channel - and supercritical flow from the adjacent basin. The influence of isolated platforms on the pathways of ocean currents and thus the distribution of erosion and the formation of various drift bodies can be investigated in data sets from the Marion Plateau along eastern Australia. The seismic stratigraphic analysis of the Yucatan Platform will also include the influence of the Caribbean current that started to flow across the Yucatan Straits about 12.5 myrs ago.

In the Petrophysics theme we continue with the petrophysical analyses of carbonate contourite drifts in cores and from outcrop samples using data from drifts in the Maldives, Maiella, Australia, and the Bahamas. By comparing and contrasting these data with the "other carbonates" from our in-house CSL data base we intend to provide criteria to discriminate carbonate drifts deposits from slope and basinal strata around carbonate platforms.

The completion of an extensive petrophysical characterization of the mudstones in the Vaca Muerta Formation provides the necessary data for a) the calibration of acoustical and electrical properties to TOC; b) quantify the anisotropy in resistivity in the mixed carbonate-siliciclastic samples, and c) determine the potential variability of TOC values derived with the ΔlogR method.

The Neuquén Basin in Argentina is the study site for the Unconventional theme. With the completion of two dissertations that include a phase of basin wide analysis of TOC, facies and mineralogy, we have reached several of our goals, which enables us to better understand the formation and distribution of these important unconventional deposits. The new projects will focus on finer-scale variability both vertically as well as laterally. In one project we evaluate the similarities and differences of compositional variations in sequences and cycles to capture vertical facies variability within the Vaca-Muerta Formation with a semi-quantitative analysis of thin sections of our measured outcrops. The second will concentrate on the lateral variability within a landing zone. The heterogeneity will be assessed along a 2 km scan line in a TOC-rich interval by measuring regularly-spaced, short (20-30 m) vertical sections along a scan line.

The addition of a geochemist expands the scope of projects in the Geochemistry and Geo-Microbiology theme. A new direction is the attempt to search for global trends in diagenesis through time using the method of rolling window regression (RWR) as a tool in identifying types of diagenetic processes. Another new direction is the comparison of various isotopic patterns in the Pacific and Atlantic and if they can survive diagenetic processes. This is important as these isotopic patterns are typically used as proxies for diagenesis and the reconstruction of ocean chemistry. The role of microbial mediation in early diagenesis of carbonates is explored in laboratory experiments in which ooid samples – one batch with the indigenous microbial community and one batch that has been sterilized – in incubation chambers are precipitating early cements.

The method of clumped isotopes (Δ_{47}), the difference between the measured and the theoretical 47/44 ratio, can be used as a temperature proxy to provide new opportunities in carbonate geochemistry. Incorporating another clumped isotope with the mass of 48 provides further refinement for geospeedometry and the determination of the burial history of carbonate containing rocks. Two projects will help calibrate Δ_{48} to temperature and the rate of change during heating. Another project then applies the clumped isotope methods in a range of different sedimentary basins with hydrocarbon production to ascertain their burial history.

Below we list the planned projects. The detailed description of each project is given in the 2020 research prospectus.

2020 PLANNED PROJECTS

MODERN AND ANCIENT CARBONATE SYSTEMS

- Sediment Budget of the Great Bahama Bank - Production and Transport
- Whitings Project Part 1: Machine Learning and the Long-Term Whitings Record
- Whitings Project Part II: Constraining the Chemistry of Inimical Waters on Great Bahama Bank
- Sedimentological Impacts of Inimical Waters on Shallow Marine Platforms: A Geochemical Perspective
- Rates of Intertidal Facies-Belt Migration from Time-Separated Remote Sensing
- A Geomodel for Subsurface Karst
- Carbonate Contourite Drift Systems – Types, Dimensions and Their Importance in Deep Water Plays
- Timing and Composition of Contourite Drifts on the Marion Plateau, NE Australia - Implications for Carbonate Platform Architecture
- Seismic Stratigraphy of the Yucatan Platform
- Towards a Depositional Model of Coarse-Grained Delta Drift Deposits, Maiella, Italy

PETROPHYSICS

- Petrophysical Characteristics of Carbonate Drift Deposits
- Calibrating Acoustical and Electrical Properties to TOC Distribution in the Vaca Muerta Formation, Neuquén Basin, Argentina

UNCONVENTIONAL RESERVOIRS

- Enhanced Outcrop to the Subsurface Correlation in the Vaca Muerta Formation
- Variability Within a Target Zone Analog of the Vaca Muerta Formation, Argentina

- Microbial Mediation on Early Cementation Processes
- Exploring Signatures of Diagenesis Using Rolling Window Regression
- Cenozoic Expression of Rolling Window Regression in Marine Carbonates Around the Globe
- Comparison of Isotopic Patterns in the Pacific and Atlantic: C and O
- Comparison of Isotopic Patterns in the Pacific and Atlantic: S, Δ_{47}, and B
- Twin Clumped Proxies and Beyond: A New Clumped Isotope Proxy, Δ_{48}
- Burial History of Reservoir Strata Using Twin Clumped Isotopes: Δ_{48} and Δ_{47}

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.

2020 REPORTING

OCTOBER 19 - 20, 2020 - ANNUAL REVIEW MEETING

The results of the projects detailed in this prospectus will be presented at the **Annual Review Meeting in Miami, October 19 - 20, 2020**. In conjunction with the meeting we offer a field trip to the mixed systems in the Dominican Republic**.** We will send out information on the logistics for the meeting in the second quarter of 2020.

OCTOBER 21 - 25, 2020 - REVIEW MEETING FIELD SEMINAR, DOMINICAN REPUBLIC, REEFS AND MIXED SYSTEMS

The Cibao Valley was at one time an open shelf and seaway along the northern margin of Hispaniola. Subsequent uplift of the island, associated with nearby plate boundary interactions, has exposed a relatively undeformed Miocene and Pliocene section. The uplifted sequence consists of a wedge-shaped deposit of Neogene marine sediment. Both siliciclastic and carbonate facies occur in the Cibao Basin, the siliciclastics shed from the adjacent Cordillera Central, and the carbonates mainly from *in-situ* skeletal precipitation. The Cibao Basin has received renewed interest with a bid licensing round launched this past July.

This fieldtrip offers insight into some fundamental questions with respect to mixed systems.

THEMES OF SEMINAR:

1) ***Cross shelf trends in mixed-system deposition*** **-** Collectively, the Cibao Valley outcrops present a spectrum of *in situ* mixing of carbonates and siliciclastics. We will examine these mixed sequences with respect to sea-level changes both regionally and locally.

2) ***Reefs in the mixed-system*** **-** Coral reefs play an important role in many tropical mixed systems both in the Tertiary, part of the Mesozoic, and the Paleozoic. The Cibao sections show several styles of reservoir-scale, reef or reef-associated lithofacies. The style of reef is largely tied to the depositional regime, which in turn is driven by changes in sea level.

3) ***Anatomy of the mixed system sequences*** **-** The Cibao Basin sections provide an ideal comparison to deposition in a pure carbonate setting such as the Bahama Banks.

Cost: Approximately $5,000; included are transportation within the Dominican Republic (mostly by boat), accommodation, meals and course notes.

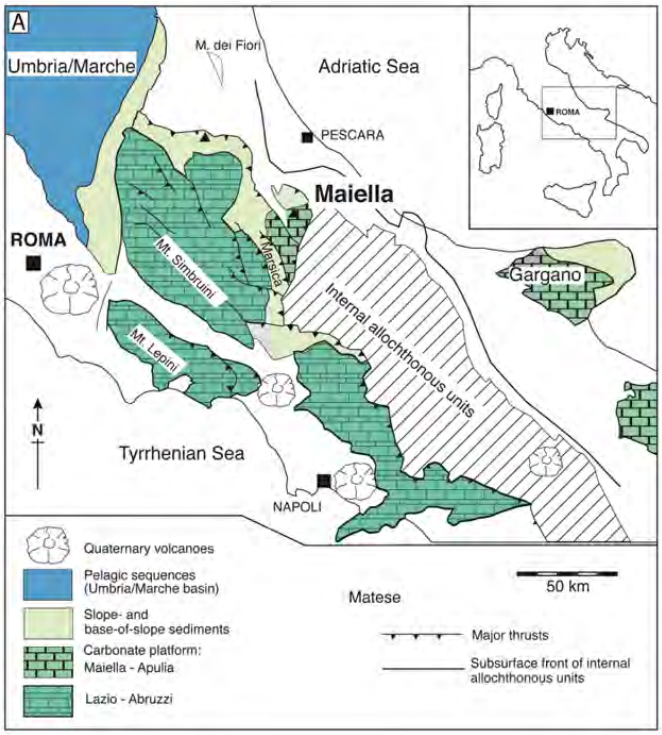
FIELD SEMINAR MAIELLA MOUNTAINS, ITALY

ANATOMY OF A CRETACEOUS CARBONATE CONTOURITE DRIFT

JULY 27-31, 2020

RATIONALE:

The Upper Cretaceous Orfento Formation in the Maiella Mountains, Italy, is recognized as a carbonate delta drift, which is a carbonate-specific contourite drift that forms where channels open into the adjacent basin (Fig. 1). These delta drifts are unique because their various flow processes deposit a coarse-grained succession that is nearly mud-free. As such they are a new depositional environment in carbonates with an excellent reservoir potential. The field seminar is intended to showcase the architecture and depositional processes that build this coarse bioclastic Upper Cretaceous delta drift.



In addition, the Maiella platform margin is a prime outcrop of an escarpment-bounded platform. Its basinal areas contain - under and above the delta drift – carbonate turbidite successions. In the Cenozoic the steep platform transitions into a ramp. We will show all these different elements during the seminar. We will visit the

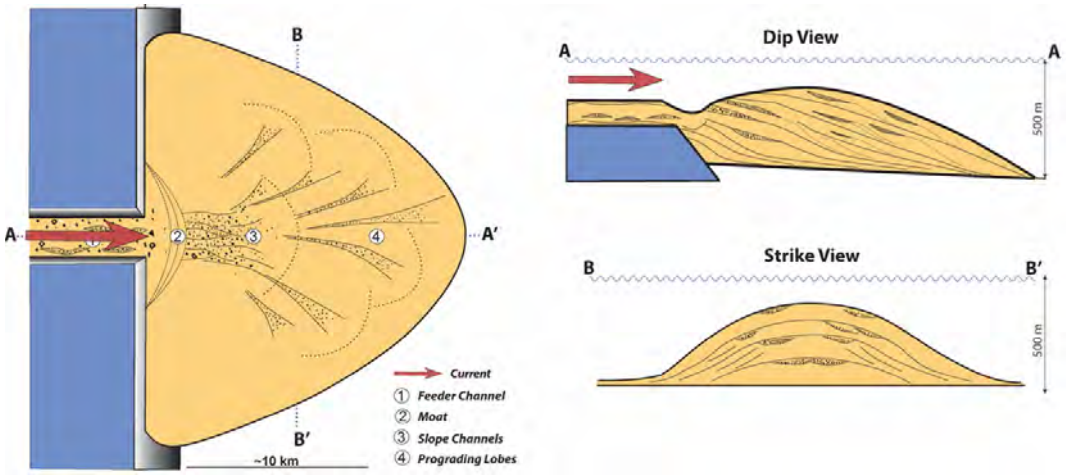
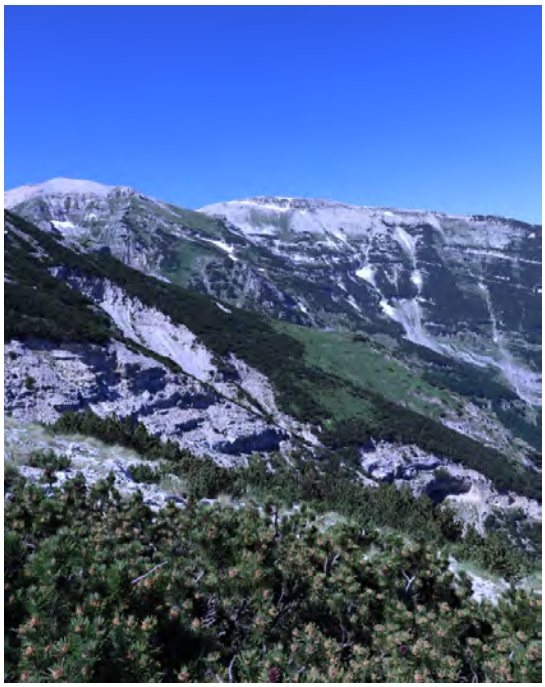


Fig. 1: Schematic display of the Maiella delta drift with a maximum thickness of 360m. 150 km² of the delta drift are exposed in the Maiella anticline and constitute about a third of the entire sedimentary body.

Madonna Della Mazza quarry where Ground Penetrating Radar surveys imaged fractures and faults in the distal portion of the delta drift. We will also present results of an infiltration experiment in the fractured strata.

ITINERARY



Monday July 27: Meet in Rome (airport) and drive to the Maiella Mountains. Introduction to the fieldtrip at Rocco Caramanico. Western face of the mountains that exposes the platform – basin transition

Tuesday July 28: Basin sections north of the escarpment in the Orfento Valley. Examine the thickest portion of the delta drift consisting of prograding coarse-grained skeletal debris (Upper Campanian-Maastrichtian Orfento Formation) in the Santo Spirito Valley.

Wednesday July 29: Overview of the platform margin, escarpment and onlapping strata then hike to the base of Mt Focalone. This location is the mouth of the current swept channel; we will visit the first thick lobe and the slope channels at Monte Cavallo.

Thursday July 30: Valley at Pennapiedimonte: Transition from deep water deposits with breccias and turbidites to the delta drift deposits and section through the delta drift into overlying Cenozoic deep water deposits.

Friday July 31: Visit to quarry at Madonna della Mazza to examine the distal portions of the delta drift and present the GPR data that images the strata but also the shear bands and fractures in the delta drift of the Orfento Formation.

Return to Rome

COST

Approximately $5,000; included are transportation in Italy, accommodation, meals and course notes.

2020 VACA MUERTA FIELD SEMINAR

CSL – Center for Carbonate Research

OUTCROP EVALUATION FOR SUBSURFACE CORRELATION OF THE VACA MUERTA FORMATION, NEUQUÉN BASIN

November 2nd to 6th, 2020

Gregor P. Eberli and Ralf J. Weger

RATIONALE:

The Vaca Muerta Formation in the Neuquén Basin has proven its unconventional resource potential. Taking advantage of the excellent exposure of the formation the CSL has assembled an outcrop data set that can be exploited as an analog to the subsurface in the Neuquén Basin. These include synthetic seismic sections by Michael Zeller and laboratory petrophysical measurements. This outcrop to seismic correlation provides a unique opportunity to understand both seismic and elastic properties of Vaca Muerta mixed siliciclastic-limestone mud rocks in the context of their outcrop expression. The aim is to use an accurate, high-resolution outcrop – subsurface correlation to highlight how geologic sections collected in outcrop can enhance the understanding of seismic-derived acoustic impedance in the foresets and bottomsets of the Vaca Muerta. In addition, our composite sections in the Puerta Curaco area provide a formidable framework for a comprehensive assessment of the distribution of the facies and total organic carbon (TOC) of the entire Vaca Muerta Formation. Here the correlation of outcrop sections to core and well-logs is achieved by measuring spectral gamma ray, TOC content and other geochemical properties with high resolution (0.5-1m spacing) in each outcrop section.

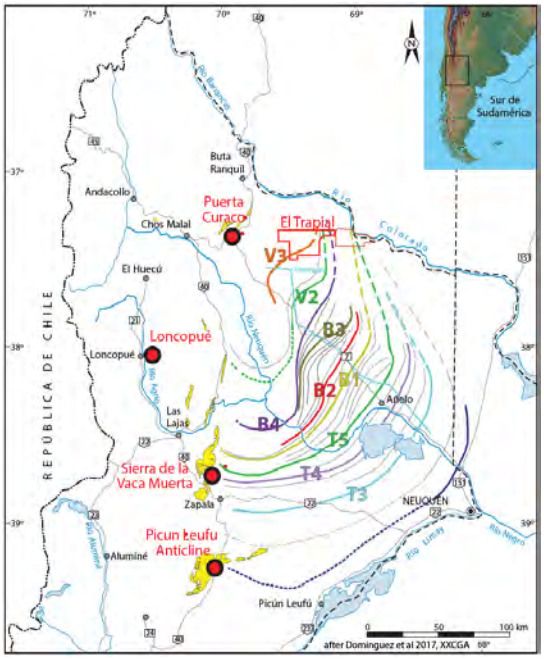


Figure 1: Basin overview map, outcrop locations, and shelf breaks (modified from Dominguez et al., 2017).

GOAL:

The main aim of this field trip in the Neuquén Basin is to demonstrate how detailed outcrop analysis can be a guide for interpreting subsurface data and potentially help to solve questions for well placement and production.

OBJECTIVES:

1. Illustrate the facies of the Vaca Muerta – Quintuco system along a proximal to distal transect and the lateral distribution and vertical variability of TOC in the basin.
2. Relate the facies and geometries to the seismic facies and correlate changes in lithology and diagenesis to chemical and petrophysical signatures measured with logging tools.
3. Discuss the outcrop-subsurface correlation based on calibration of outcrop geometry and lithology logs to subsurface logs and synthetic seismic sections.

LOCATION:

The seminar begins and ends at the airport in Neuquén, Argentina. Field stops at different outcrops in the south of the basin (Picun Leufú and Sierra de la Vaca Muerta) illustrate facies distribution and sequence stratigraphic architecture of the Vaca Muerta System in the southern clinoforms. Well-exposed outcrops in the Puerta Curaco (PC) area further north contain the complete section of the organic-rich basinal facies. Across the three different outcrop locations, you will observe the facies in the prograding clinoforms from the topset (shelf), to the foreset, and finally a basinal bottomset. The Sierra de la Vaca Muerta area offers great insight into the progradational style of the Vaca Muerta-Quintuco system especially the time transgressive nature of the different facies. The transect will document that the high TOC content is not restricted to a unique stratigraphic level but is a recurring pattern within the prograding depositional system, resulting in multiple organic-rich zones in similar sequence stratigraphic positions in each sequence. In addition, we will demonstrate the subtle variability of organic and carbonate content in different types of siliceous to more cemented mudstones. The outcrops also provide a 2-D view away from the section that is equivalent to having lateral view around a well.

ITINERARY:

Day 1: Arrival in Neuquén, introduction
Day 2: Travel Neuquén – Zapala, Picun Leufu Anticline
Day 3: Sierra de la Vaca Muerta, base of the Vaca Muerta, Travel to Chos Malal
Day 4: Basinal sections at the Puerta Curaco – Yessera del Tromen area
Day 5: Younger successions at Puerta Curaco and return to Neuquén

WHO SHOULD ATTEND:

Exploration and production geoscientists and reservoir engineers working in the Vaca Muerta or in unconventional mixed system reservoirs around the world.
Costs: $6,500 (USD), Includes all ground transportation, lodging, meals, course notes, and relevant presentations and posters in digital form.

CONTACTS:

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Registration/Payment: **Before Sept. 25th, 2020**

Important Note: A minimum of 12 attendees will be required for this trip.

UNIVERSITY OF MIAMI
ROSENSTIEL SCHOOL of MARINE & ATMOSPHERIC SCIENCE

Department of Marine Geosciences
University of Miami

CSL
CENTER FOR CARBONATE RESEARCH

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 2020. 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:

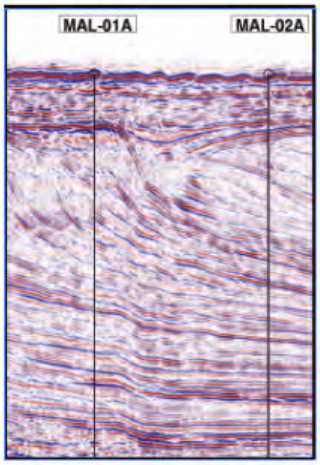
Geoscientists/students will learn to incorporate the acquired knowledge and available data and tools into the workflow of applied projects.

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 Carboante Cores

MGS 789 2 Cr Petroleum Geology in Carbonates

For additional information about the CSL - Center for Carbonate Research or the Certificate Program Applied Carbonate Geology please contact:

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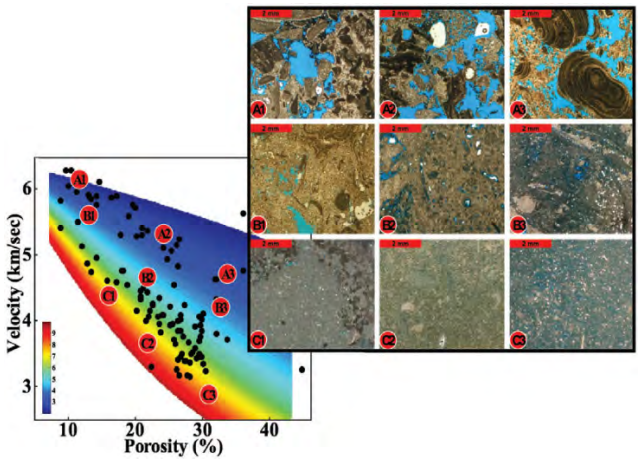

RESEARCH PROJECT DESCRIPTIONS

Modern and Ancient Carbonate Systems

SEDIMENT BUDGET OF THE GREAT BAHAMA BANK - PRODUCTION AND TRANSPORT

Cecilia Lopez-Gamundi, Gregor P. Eberli, [1]Thomas Dobbelaere, [1]Emmanuel Hanert, Paul (Mitch) Harris, and Sam Purkis
[1)] *Université Catholique De Louvain, Belgium*

PROJECT OBJECTIVES

- To conduct a GBB-wide sediment budget analysis and reconcile sediment production with sediment accumulation.
- To assess the influence of hydrodynamics on sedimentary facies distribution and on and off-platform sediment transport.
- To quantify the importance of uniformitarian versus catastrophic (storm) events on the sedimentary processes of GBB.

PROJECT RATIONALE

Recent GBB sedimentological studies have primarily focused on either examining platform sediment production, mapping of on and off-platform sediment distributions, or analyzing variable filling of accommodation space. However, a new, integrative GBB-wide sediment budget analysis has yet to be conducted. SLIM numerical hydrodynamic modelling (developed at the Université Catholique de Louvain, Belgium) indicates that the current velocities induced by fair-weather conditions on the platform top are too lethargic to resuspend meaningful volumes of sediment. Storm-weather conditions, however, resuspend a great deal. Elevated current velocities during and shortly after storms are consistent with satellite-based observations of suspended sediment (Fig. 1).

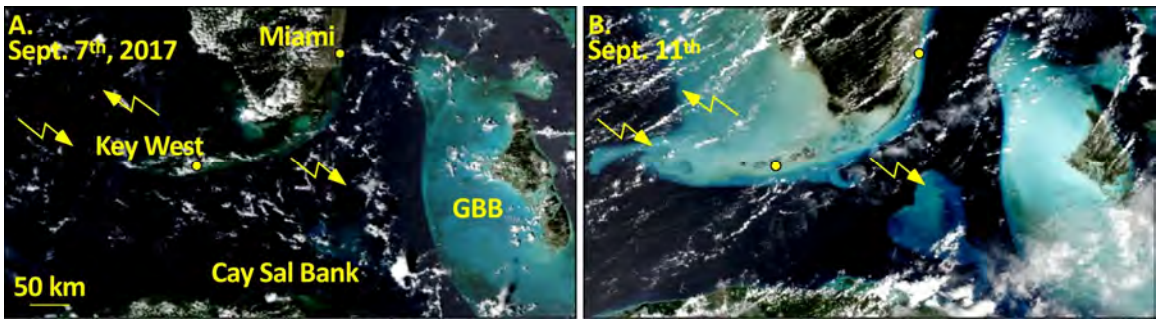

Figure 1. Waters around the southern tip of the Florida Peninsula, Straits of Florida, Great Bahama and Cay Sal Banks before (A. Sept. 7th, 2017) and after (B. Sept. 11th, 2017) the passage of Hurricane Irma (Sept. 9-10th, 2017) as captured by the VIIRS instrument on the NOAA/NASA Suomi NPP satellite. The hurricane is seen to loft vast sediment plumes from the West Florida Shelf, Great Bahama and Cay Sal Banks which become entrained in the Florida Current. It is postulated that during such events, meaningful quantities of sediment are lost from the Bahamas platform tops and redeposited on the slopes and beyond. Hurricanes might exert important control on the sediment budget of carbonate platforms. Yellow arrows equally positioned in A. and B. for comparison. North is top.

Although the dominant mechanism behind off-platform sediment transport, uniformitarian versus catastrophism, remains unknown, large volumes of platform-top derived sediment have been mapped on the platform's flanks. Further, the sediment architecture and facies of the flanks indicate substantial along strike-variability (e.g. Anselmetti et al., 2000; Mulder et al., 2012; Schnyder et al., 2018). Building off the substantial research conducted by our CSL collaborators past and present, we aim to quantify the relationship between prevailing sedimentation and hydrodynamic flow on and off platform. Through this multiple dataset comparison, we will determine the amount of sediment being produced atop the GBB, quantitate the sediment transport by currents, measure off-platform sediment volumes, and conduct a comprehensive sediment budget for GBB.

APPROACH

Environmental facies delineated by satellite imagery have been populated with literature-based sediment production rates assembled to produce yearly total sediment production estimates. The SLIM hydrodynamic model is being used to examine the likely fate of platform-produced sediment during fair and storm-weather conditions alike. Model outputs will then be compared to satellite audits of total water column suspended sediment concentrations, as well as CHIRP sub-bottom and seismic data acquired on the western slope of GBB.

SIGNIFICANCE

An understanding of sediment production and water movement atop the GBB is paramount to understanding the volumetric significance of sediment dispersal. These processes exert physical control over platform-top sedimentation, which, in turn, govern slope architecture, and the along-strike variability in that architecture. The investigation of both sediment production and accumulation in a hydrodynamic context allows for a novel carbonate source-to-sink analysis.

REFERENCES

Anselmetti, F.S., Eberli, G.P., Ding, Z.D., 2000, From the Great Bahama Bank into the Straits of Florida: a margin architecture controlled by sea-level fluctuations and ocean currents. Geological Society of America Bulletin 112:829-844.

Mulder, T., Ducassou, E., Eberli, G.P., Hanquiez, V., Gonthier, E., Kindler, P., Principaud, M., Fournier, F., Léonide, P., Billeaud, I., Marsset, B., 2012, New insights into the morphology and sedimentary processes along the western slope of Great Bahama Bank. Geology 40:603-606.

Schnyder, J.S., Eberli, G.P., Betzler, C., Wunsch, M., Lindhorst, S., Schiebel, L., Mulder, T., Ducassou, E., 2018, Morphometric analysis of plunge pools and sediment wave fields along western Great Bahama Bank. Marine Geology 397:15-28.

WHITINGS PROJECT PART 1: MACHINE LEARNING AND THE LONG-TERM WHITINGS RECORD

Sam Purkis, Amanda Oehlert, Heather Hunter, Peter K. Swart, [1]Thomas Dobbelaere, [1]Emmanuel Hanert, and Paul (Mitch) Harris

[1)] *Université Catholique De Louvain, Belgium*

PROJECT OBJECTIVES

- Deploy a neural network to identify whitings in daily MODIS ocean-color imagery over timescales of decades.
- Examine the whiting record for seasonal and multi-year trends and explore their controls.
- Develop an understanding of the variability of non-skeletal mud production through time and its influence on platform-top sedimentology.

PROJECT RATIONALE

The term "whiting" has been used to describe occurrences of lime mud precipitated directly from both marine and fresh waters. As a result of the potential of whitings to contribute to the Bahamas sedimentary record (e.g. Turpin et al., 2011; Purkis et al., 2017), considerable effort has been applied to understand the triggers and mechanisms of precipitation in this locality – a debate that has continued for more than eighty years.

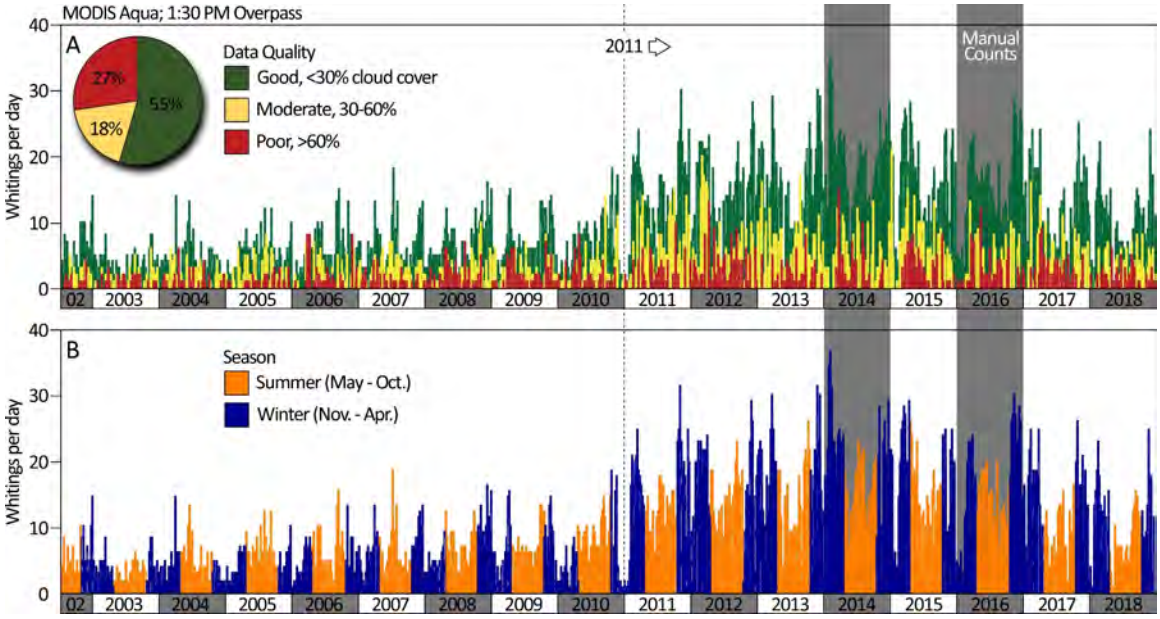

Figure 1: Whitings atop GBB tallied via a convolutional neural network from 2003 through 2018. (A) Data quality partitioned by cloud contamination and (B) summer-winter trends across the data series.

Recent work by the group has yielded a machine-learning algorithm capable of automating the identification of whitings from satellite imagery. Preliminary tests with this algorithm have allowed whitings to be mapped from the twice-daily MODIS overpasses from 2003 through 2008, a record of nearly 55,000 precipitation events (Fig. 1). These new data have the ability to greatly refine the understanding of the spatial and temporal distribution of whitings across Great Bahama Bank and beyond.

APPROACH

This study will call upon a newly developed Convolutional Neural Network (CNN), which is a class of deep neural networks, most commonly applied to analyzing visual imagery. The algorithm has been tested on MODIS imagery for Great Bahama Bank (GBB) and preliminary results suggest it to be capable of resolving whitings down to 250 sq. m with an accuracy exceeding 85%. The CNN has been trained on manual digitizations of whitings conducted for daily imagery acquired in 2014 and 2016, a training set of 15,000 events. The algorithm has now been used to map an additional 50,000 whitings and will shortly be updated to audit their shape and area, as well as their location.

SIGNIFICANCE

Preliminary results suggest that the summer-winter cycle in the abundance of whitings reported by Purkis et al. (2017) generally persists throughout the 2003 through 2018 record, but is augmented by a longer-term oscillation in frequency which can be observed in the near doubling of average annual GBB whitings after 2011 (Fig. 1). Possible controls on the decadal cycling of Bahamas lime mud production will be assessed and the geological implications for platform-top facies heterogeneity will be explored.

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WHITINGS PROJECT PART II: CONSTRAINING THE CHEMISTRY OF INIMICAL WATERS ON GREAT BAHAMA BANK

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PROJECT OBJECTIVES

- Evaluate the impact of variable geochemistry of waters from the Straits of Florida on lime mud formation on Great Bahama Bank.
- Refine numerical models of aragonite saturation in the Whitings Zone.
- Examine spatial trends in stable isotope and trace element geochemistry of carbonate muds on Great Bahama Bank.
- Assess the role of 'inimical waters' on whitings formation.

PROJECT RATIONALE

Understanding the physical, chemical, and biological processes that form whitings in the Modern may provide key insight into the significance of geochemical signatures of lime mud in the ancient geological record. If whitings are created through the breakdown and resuspension of larger biotic grains (Broecker and Takahashi, 1966; Morse et al., 1984; Trower et al., 2019), their geochemical signature must be interpreted to reflect a confluence of environmental conditions, vital fractionation effects, and a longer period of time integration. In contrast, water column precipitates (Shinn et al., 1989; Robbins and Blackwelder, 1992; Robbins et al., 1997; Swart et al., 2014; Purkis et al., 2017) would represent instantaneous snapshots of water column chemistry with possible biological influence. Given the large quantities of lime mud in the geological record, understanding the significance of their isotopic and elemental signatures can generate new perspectives into biogeochemical cycling in early Earth history.

Figure 1: CTD Rosette onboard the R/V F. G. Walton Smith, which was used to sample water masses at various depths within the Straits of Florida on October 13, 2019.

APPROACH

In order to better constrain the geochemistry of the water masses that are mixed in the Whitings Zone, we will collate analyses of both unpublished CSL data and new samples from the Straits of Florida. Surface water samples were collected across the western half of the Florida Current in the Straits of Florida in October 2019. In addition, discrete water samples were collected for geochemical characterization using a CTD at the Hansell Oceanographic Site in the Straits of Florida (Fig. 1). These new water samples will be analyzed for alkalinity, DIC, and trace elements to better constrain the chemistry of the off-bank water masses at various depths. Our numerical models of saturation state will be refined for each mixing proportion using these datasets. Finally, we will conduct a geochemical characterization of the mud-sized fraction of surface samples on Great Bahama Bank including trace metals and rare earth element concentrations.

SIGNIFICANCE

Preliminary results suggest that the higher abundance of winter whitings is a consistent phenomenon over the past 15 years (Purkis et al., 2019), supporting the interpretation that the formation of inimical bank top waters plays a role in whiting formation. Refined numerical models of water chemistry and enhanced geochemical characterization of mud on Great Bahama will be used to elucidate processes of whiting formation that will enhance our understanding of the significance of geochemical records from lime mud through geological time.

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SEDIMENTOLOGICAL IMPACTS OF INIMICAL WATERS ON SHALLOW MARINE PLATFORMS: A GEOCHEMICAL PERSPECTIVE

Colleen Brown, Sam Purkis, and Amanda M. Oehlert

PROJECT OBJECTIVES

- Isolate geochemical signatures of coral fragments, crustose coralline algae (CCA), and surrounding sediments.
- Quantify geochemical signatures including; $\delta^{13}C_{carb}$, $\delta^{18}O$, $\delta^{13}C_{org}$, $\delta^{15}N_{org}$, total organic carbon (TOC), total nitrogen, concentrations of phosphorus, trace metals, and rare earth elements.
- Assess covariation between $\delta^{13}C_{carb}$ and $\delta^{13}C_{org}$ in reef rimmed settings.
- Discuss the impact of inimical water formation on the sedimentology, geochemistry, and margin development of shallow marine carbonates.

PROJECT RATIONALE

The formation of colder winter waters ('inimical waters' *sensu* Ginsburg & Shinn, 1964; Schlager, 1981) has recently been interpreted to exert an influence on the sedimentology of shallow carbonate environments in the subtropics (Purkis et al., 2019). Sedimentological and geochemical analyses of the surface sediments on Great Bahama Bank (Reijmer et al., 2009; Swart et al., 2009; Oehlert et al., 2012) have characterized sediments produced in a subtropical setting that is influenced by inimical waters in the winter months. In contrast, similar efforts to characterize tropical, reef-rimmed platforms that are not influenced by inimical winter waters have yet to be conducted. In this study, geochemical analyses, including stable isotopes and trace element concentrations, will be conducted and integrated with sedimentological evaluations conducted previously on surface sediments from Fakarava and Rangiroa, two reef rimmed atolls in the Tuamotu Archipelago in French Polynesia. These results will be compared to published studies of Great Bahama Bank and interpreted as two endmembers in a gradient of inimical water formation and platform top sedimentology.

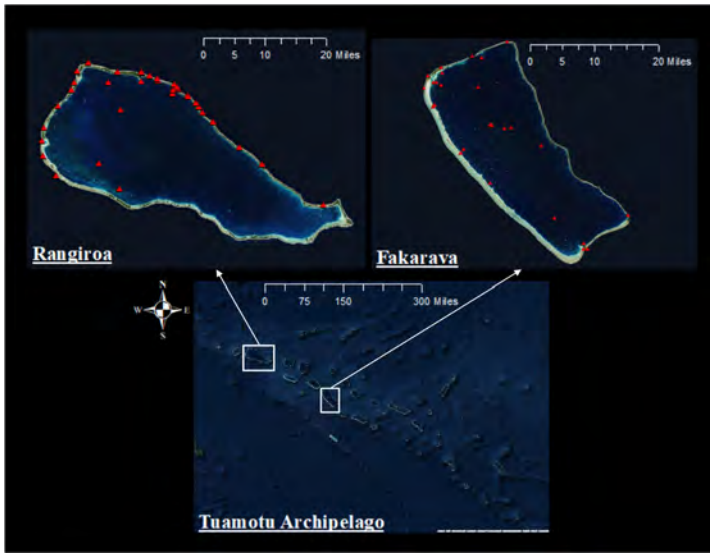

Figure 1: Study sites, Rangiroa and Fakarava, Tuamotu Archipelago. Red triangles denote sediment sampling sites.

APPROACH

To identify the geochemical signatures of sedimentary components of two atolls in the Tuamotu Archipelago, Fakarava and Rangiroa. Surface sediments for both atolls, collected by the Living Oceans Foundation (Fig. 1), will be separated into bulk sediment, coral fragments, and CCA. Each subset will be analyzed for $\delta^{13}C_{carb}$, $\delta^{18}O$, $\delta^{13}C_{org}$, and $\delta^{15}N_{org}$ values, as well as trace and rare earth element concentrations.

SIGNIFICANCE

Inimical waters are created when water masses atop shallow platforms are chilled during winter months in the subtropics, conditions that have been interpreted to promote enhanced mud formation on Great Bahama Bank (Purkis et al., 2019). Previous researchers have noted the negative impact that inimical waters can have on the development of coral reefs (Ginsburg and Shinn, 1964; Schlager 1981, Purkis et al., 2014), using this observation as evidence for limited reef development outside of the modern tropics. Given this duality, it is plausible that inimical waters play an important role in driving the style of sedimentation, and thus style of platform, that develops through geological time. If this observation is applicable to the geological record, it has implications for the distribution and interpretation of geochemical signatures in sediments from deeper, coral-reef rimmed platforms compared to those formed in shallower, open-margin platform settings.

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RATES OF INTERTIDAL FACIES-BELT MIGRATION FROM TIME-SEPARATED REMOTE SENSING

Mingyue Wu and Sam Purkis

PROJECT OBJECTIVES

- To employ time-separated remote sensing to quantify rates of facies migration over multiple decades in the Andros tidal-flats of Great Bahama Bank.
- To explore the geological implications of facies dynamics on subsurface analogs.

PROJECT RATIONALE

The proposed work, which will consider a low-energy carbonate depositional system, follows a study which considered the dynamics of high-energy grainy facies in the Chagos Archipelago (Indian Ocean). A key finding of the Chagos work was that facies migration is controlled by the physical environment and wave energy, in particular. Whereas the Andros tidal flats are not subject to meaningful wave energy, we hypothesize that their dynamics are similarly controlled, as has been reported in analogous studies. Facies-belt dynamics are poorly understood at timescales of decades to centuries because of the lack of quantitative data spanning these time periods. A wealth of vintage-military aerial photography acquired in the 1940s can be paired with modern high-resolution satellite imagery to quantify temporal change to allow meaningful extrapolation to geological timescales. We have remote sensing data spanning 75 years for the Andros tidal flats (Fig. 1).

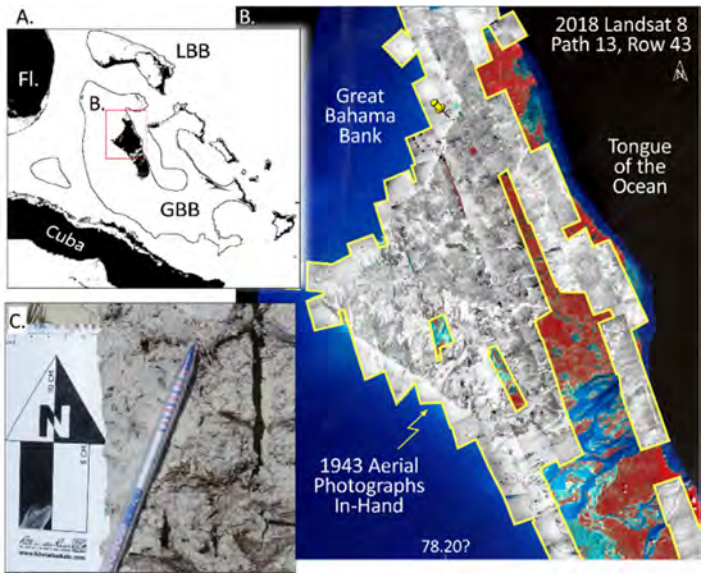

Figure 1. The Andros Island tidal flats. (A) Andros Island is the largest landmass atop the GBB. (B). Red color in this 2018 Landsat image denotes vegetation. The yellow polygon denotes coverage by 1943 aerial photographs acquired by the Royal Airforce against which landform change can be quantitatively assessed over 75 years. (C) A core sample acquired in 2019 (location marked by yellow pin in B) located within an abandoned tidal channel. Note 'sediment lag'-gastropods indicative of high-energy conditions prior to channel abandonment.

Beyond quantifying rates and motifs of facies migration, this project will examine the role of emergent behavior in structuring intertidal carbonates. Systems displaying emergent behavior manifest significantly different characteristics from those resulting from simply adding up all the constituent parts - an example being how small perturbations can have radical consequences to the system's overall depositional architecture. Whereas numerical modelling by Fagherazzi (2008) demonstrates emergent behavior in intertidal siliciclastic deposits, its presence in equivalent carbonate environments remains controversial. For instance, coring conducted by Shinn et al. (1969) suggests frequent reconfiguration of the Andros tidal flats, an observation in conflict with studies conducted by Rankey (2002), Maloof and Grotzinger (2012) who conclude long-term stability of the tidal-flat architecture. We aim to resolve this contradiction.

APPROACH

Following the protocols of Purkis et al. (2016), the tidal channels will be manually extracted from the vintage and modern imagery. Calibration for the interpretation of the remote sensing data is provided by field observations from a recent fieldtrip to the Triple Goose Creek area which consists of GPS measurements, short cores, and abundant digital photographs. Drivers of the change in facies configuration through time will consider allogenic factors, such as gradients in prevailing hydrodynamic energy, as well as autogenic processes, such as organism-environment feedbacks.

SIGNIFICANCE

Migrating facies belts deliver lateral and vertical heterogeneity in carbonate deposits which can be difficult to replicate using forward models. Autogenic dynamics are particularly poorly understood, yet, through emergent behavior, are capable of spontaneously producing coherent spatial facies patterns through internal interactions. Understanding these processes and their characteristic length and time-scales has the potential to yield insight into the variability of depositional facies that consistently challenge outcrop and subsurface interpretations.

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A GEOMODEL FOR SUBSURFACE KARST

Lisa Tanh, Michael Zeller, Fabio Lapponi, Gregor P. Eberli, and Sam Purkis

PROJECT OBJECTIVES

- To develop a geomodel of karst occurrence calibrated from a doline analysis from the Nullarbor Plain, Australia.
- To populate the geomodel with additional examples of karstified areas, both modern and subsurface, i.e. Spain and Yucatan.
- To apply the geomodel to a subsurface example using extracted seismic attributes such as faults, fractures, and seismically-resolvable dolines.

PROJECT RATIONALE

Accurate maps of the subsurface distribution of karst are important for mitigating geohazards and understanding reservoir connectivity. Often obscured in seismic data, karst cannot always be mapped directly (Grasmueck et al., 2013) and it is here that geostatistical models can be used to simulate its likely distribution, including the size, shape, orientation, and clustering of dolines. Machine-learning algorithms that utilize spatial data for predictive purposes are common in ecological modeling (Schratz et al., 2018). By using a database populated with doline morphometric parameters, these modeling methods will apply to geologic modeling of lateral karst occurrence. This was the motivation for a study in the Nullarbor Plain of Australia, which has provided a rich database of doline morphometric characteristics and their tectonic controls across a wide area (2,500 sq. km) with a broad diversity in the motif of surficial karst.

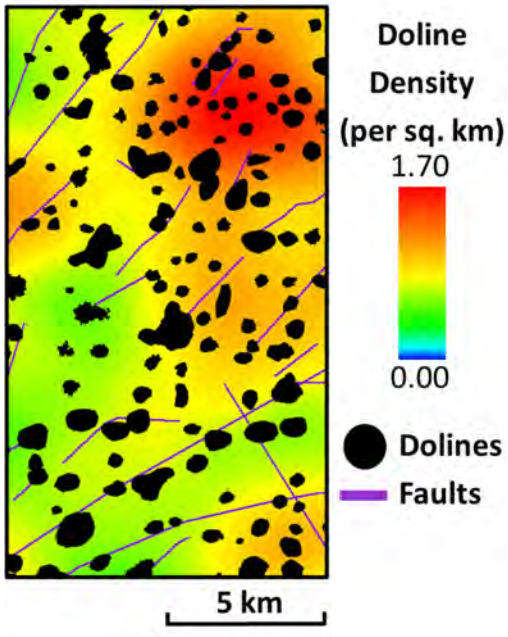

Figure 1: An example of a heat map within the Nullarbor Plain depicts density of dolines per sq. km. Areas with small dolines are more intensely karstified than areas with large dolines.

APPROACH

Depressions were automatically extracted and manually mapped from digital terrain models (DTMs) for a total 2,500 sq. km area of the Nullarbor Plain. These dolines were quantified based on morphometric and spatial attributes. Tectonic and geomorphologic controls were then mapped from DTMs and Total Magnetic Intensity data. The relationship between these controls and the subsequent dolines was quantified.

Following the protocols of Zhu et al. (2016) and Schratz et al. (2018), doline parameters of the Nullarbor act as predictive variables for spatial distribution of karst in the subsurface. Furthermore, the key to developing such

models is the analysis of a broad portfolio of analogs which can be mapped to provide the spatial statistics necessary to populate a geo-model. Surficial karst mapping will expand beyond Australia to encompass additional surficial and subsurface karst landscapes, such as Spain and the Yucatan. With these data, a geomodel will be developed to back-solve the distribution of karst in areas which cannot be readily remotely sensed, including the subsurface. Parameters that are known to exert control on karst distribution, such as faults and fractures (Guidry et al., 2007), and a partial understanding of the existing karst system, such as the presence of isolated large dolines (Harris et al., 2018) will be extracted from seismic data to guide the probability of doline encounter.

SIGNIFICANCE

Parameters that are known to exert control on karst distribution such as faults and fractures and existing large dolines are routinely extracted from seismic data (Russel-Houston and Gray, 2014). By applying a karst-occurrence geomodel, the occurrence of smaller dolines that are more frequent, but often fall below seismic resolution, can be predicted. This strategy will aid in the avoidance of geohazards as well as providing an enhanced understanding of the heterogeneity of subsurface reservoirs.

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CARBONATE CONTOURITE DRIFT SYSTEMS – TYPES, DIMENSIONS AND THEIR IMPORTANCE IN DEEP WATER PLAYS

Gregor P. Eberli and Sara Bashah

PROJECT OBJECTIVES

- Continue assembling a data base of carbonate contourite systems that includes their dimensions and sedimentary characteristics.
- Use data base for a comprehensive overview of carbonate contourite drift systems.
- Evaluate current-related erosion and deposition with regard to reservoir and seal capacity.

PROJECT RATIONALE AND GOALS

The systematic study of siliciclastic contourite drift systems over the last 20 years has led to a recognition of the importance of bottom currents in deep sea sedimentation both on a bed scale (contourite) and on the large, generally fine-grained, sedimentary bodies (contourite drifts) deposited by bottom currents (Rebesco et al., 2014). Several research expeditions to carbonate provinces provide now the information to also comprehensively describe carbonate contourite systems (Betzler et al., 2014, Eberli and Betzler, 2019). One big difference is the exposure of the carbonate system to surface currents and interaction between carbonate buildups and currents that produces carbonate specific drift bodies (Fig. 1). In addition, surface currents distribute carbonates on volcanic edifices and basement highs to produce coarse-grained facies belts that do not fit into existing depositional models.

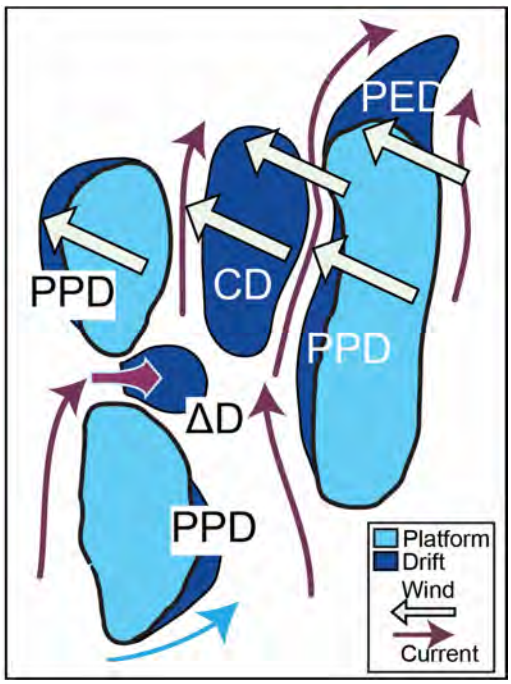

Figure 1: Three carbonate-specific types of contourite drifts that develop because of a feedback between steep morphology and sediment production and delivery to the adjacent currents.

Periplatform drifts (PPD) *form as currents hugging the slopes of carbonate platforms move offbank-transported sediment.*

Platform edge drifts (PED) *form at the confluence of currents flowing around platform edifices. They receive the sediment mostly from the adjacent platform.*

Delta drifts (DD) *is the product of (semi-) continuous flow through a channel that opens into a deeper basin.*

Thus, one goal of this ongoing project is to assemble a data base of carbonate contourites drift systems that includes their dimensions and relates the architecture and composition to the oceanographic setting. A second goal is to evaluate the carbonate drift systems with regard to their reservoir and seal capacity.

This second goal is prompted by the recognition of the importance of ocean currents within petroleum systems that has led to the discoveries of giant reservoirs like the Coral and Mamba fields offshore Mozambique (Fonnesu et al. 2020). It is highly likely that the interaction between gravity flows and currents will generate similar plays in deep-water carbonates.

DATA SETS

Seismic and multibeam data collected in expeditions by colleagues from Germany and France to the Bahamas, the Gulf of Mexico, Maldives and the Marion Platform are available for this study. Published data sets from the Caribbean, South East Asia and ancient carbonate contourite drift systems will be incorporated to assemble a comprehensive data base on carbonate contourite drift systems.

This information will be utilized to develop models of current-controlled erosion and deposition in carbonates that take into account the carbonate-specific characteristics of sediment production, grain density, and topography. These models will then be compared to depositional models in siliciclastic environments.

SIGNIFICANCE

Incorporating and/or testing a current control on the deposition of carbonates potentially improves depositional models of slope and ramp carbonates. Carbonate slope models until recently mostly considered gravity flows to be the main factor controlling distribution. Documentation of ocean currents in relatively shallow water (<300m water depth) indicates that incorporating currents as a sediment distributor might improve the existing models such as the "carbonate ramp" on seamounts and volcanic islands.

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TIMING AND COMPOSITION OF CONTOURITE DRIFTS ON THE MARION PLATEAU, NE AUSTRALIA - IMPLICATIONS FOR CARBONATE PLATFORM ARCHITECTURE

Sara Bashah and Gregor P. Eberli

PROJECT OBJECTIVES

- Relate composition, shape, and dimension of various drift deposits on the Marion Plateau to current processes.
- Investigate the timing of the onset of the East Australian Current based on the contourite drift deposits on the Marion Plateau.
- Assess the relative importance of oceanographic factors relative to sea level and tectonics on the evolution of carbonate platforms.

PROJECT RATIONALE

Progressive development of the East Australian Current are recorded in the contourite drifts deposited on the Marion Plateau (Isern et al., 2004; Eberli et al., 2010). These drift packages (Fig. 1) record the paleo-circulation, which responded to both local rifting events and the northward movement of the Indo-Australian plate (Isern et al., 2002). However, the drift architecture and depositional stages of these drift deposits need to be revisited to understand the hydrodynamic regime of the western Coral Sea and its influence on the drowning of the Marion Plateau carbonate platforms. Updating the ages of the drift deposits will bring new understanding to the significance of the current flow intensity in the context of major global oceanic, tectonic, and climate events and on the evolution of the Marion Plateau carbonate platform system.

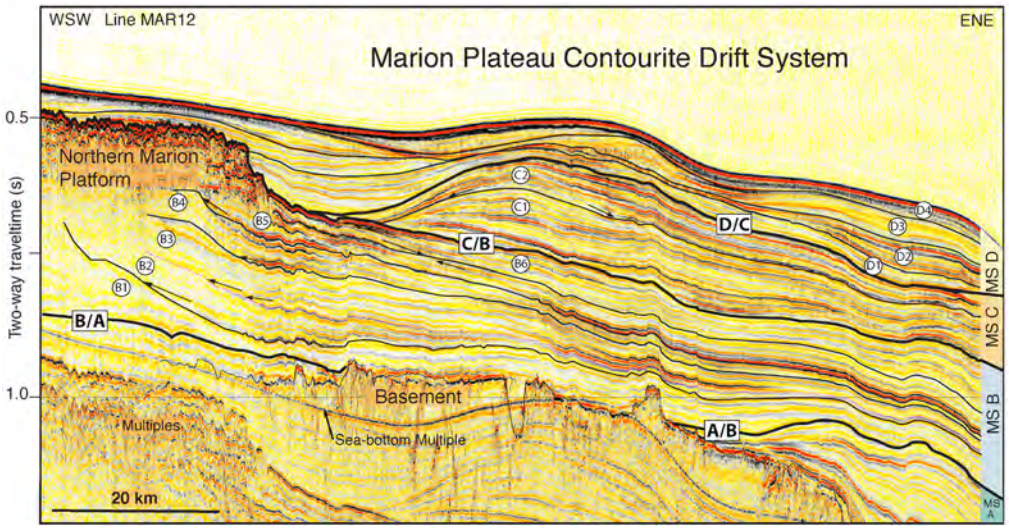


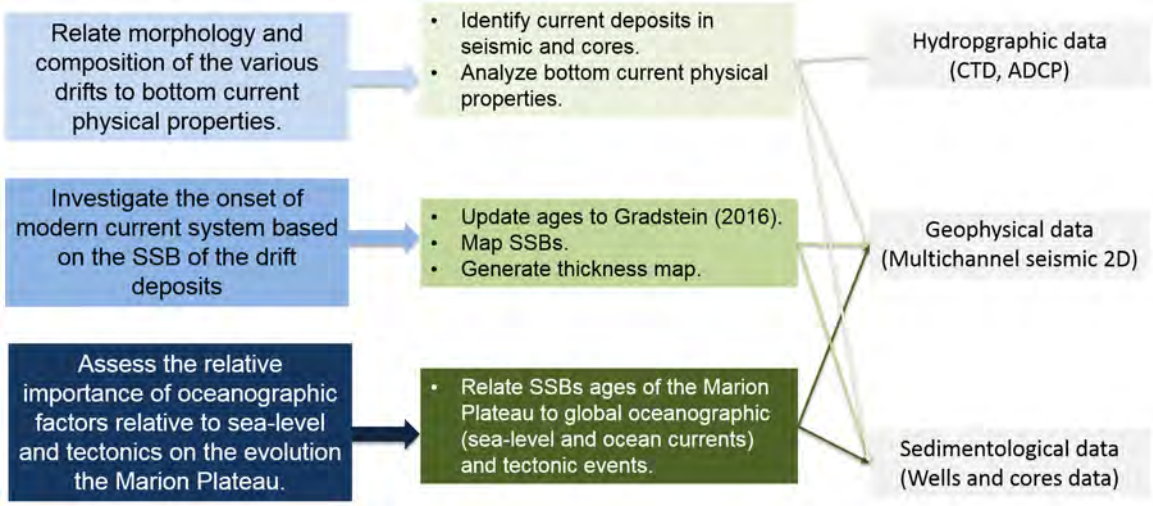
Figure 1: Seismic data displaying a central transect across the Marion Plateau. Four megasequences (A-D) are subdivided into 14 unconformity-bounded sequences. The two youngest megasequences C and D are contourite drift sequences in which numerous downlap surfaces separate individual drift packages (modified from Eberli et al., 2010).

DATA SETS

For this study three data sets, consisting of seismic, cores, and log data, from ODP Leg 194 and ODP Leg 133 are analyzed. Age models are based on biostratigraphy and Sr-isotope dating from eight sites drilled during ODP Leg 194, and two sites drilled during ODP Leg 133.

APPROACH AND WORKFLOW

To achieve the goals regarding the onset and composition of the contourite deposits, and their influence on platform architecture, the following workflow will be applied.



SIGNIFICANCE

The outcome of this study will add information towards a comprehensive understanding of the influence of currents on carbonate platform architecture. This knowledge potentially helps to discriminate current-influenced platforms from those evolving during times with less ocean circulation.

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SEISMIC 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.
- Map the seismic sequences in the intraplatform seaway of the Yucatan Platform.
- Place the evolution of the Yucatan Platform into the regional context of Caribbean tectonics.

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 up to 40 km of the underlying basement and created a multi-ring crater 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 depression is filled with prograding clinoforms starting probably as early as Early Eocene (Whalen et al., 2013, Canales-García et al., 2018). The boundary between the Cretaceous and the Paleocene strata is a well-defined seismic horizon. The Cretaceous strata displays faults and deformation that are reminiscent of wrench faults. The question is how much

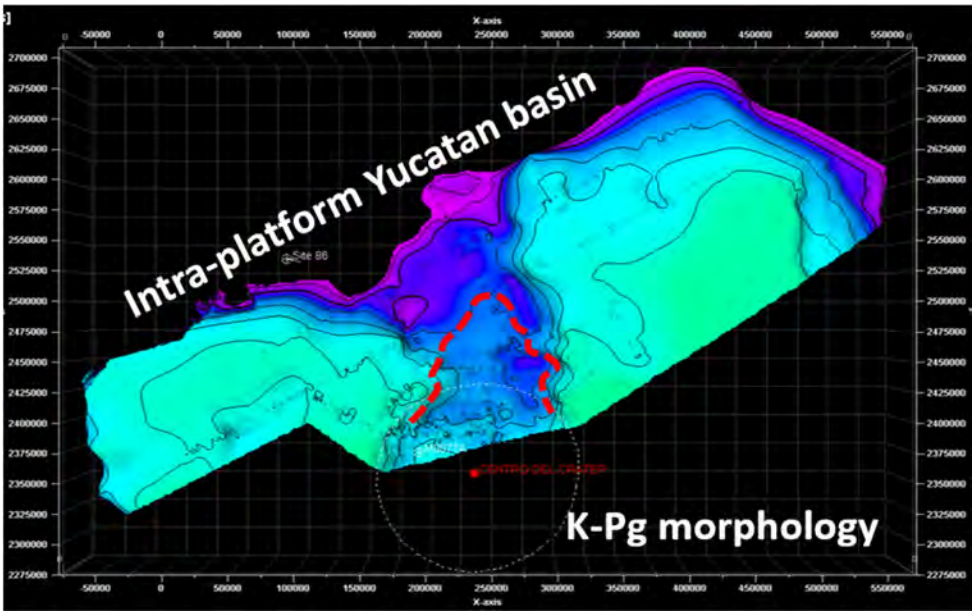

Figure 1: Topography of the Yucatan Platform at the Cretaceous-Paleogene boundary, displaying the roughly north-south oriented Intraplatform Yucatan Basin, which is nearly 180 km wide and up to 1200 m deep (from Guzman et al., 2019).

of this deformation is the result of the asteroid impact and how much is related to changes in the regional stress regime. This project aims to assess the structural evolution of the Yucatan Platform and also to analyze the prograding sequences with regards to sea-level control. 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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TOWARDS A DEPOSITIONAL MODEL OF COARSE-GRAINED DELTA DRIFT DEPOSITS, MAIELLA, ITALY

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

PROJECT OBJECTIVES

- Test the hypothesis that stratal succession of the delta drift in the Maiella is the combined product of hyperpycnal flow originating from the semi-continuous current flowing through the feeder channel and supercritical flow in the adjacent basin.
- Visualize the distribution of clasts in 3D to better elucidate erosion and transport mechanisms.
- 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.

PROJECT RATIONALE

The Orfento Formation in the Maiella Mountains (Italy) is a largely mud-free succession with sedimentary structures that indicate deposition from a variety of subaqueous high-density sediment flows. Yet, the succession does not fit in any of the existing turbidite models, and as a result has, hitherto, been variously interpreted as a succession of sea-level controlled slope deposits, a shoaling shoreface complex, or a carbonate tidal delta. Due to the similarities in geometry and facies of the Orfento Formation to the contourite delta drift in the Maldives (Fig. 1), these deposits are now recognized as a Cretaceous delta drift (Eberli et al., 2019).

What is still underexplored are the flow mechanisms that act within a current-controlled delta drift. Contourite drift deposits are typically fine-grained but the carbonate delta drifts in the Maldives and the Maiella are, especially in the proximal parts, coarse-grained nearly mud free deposits. Many beds display

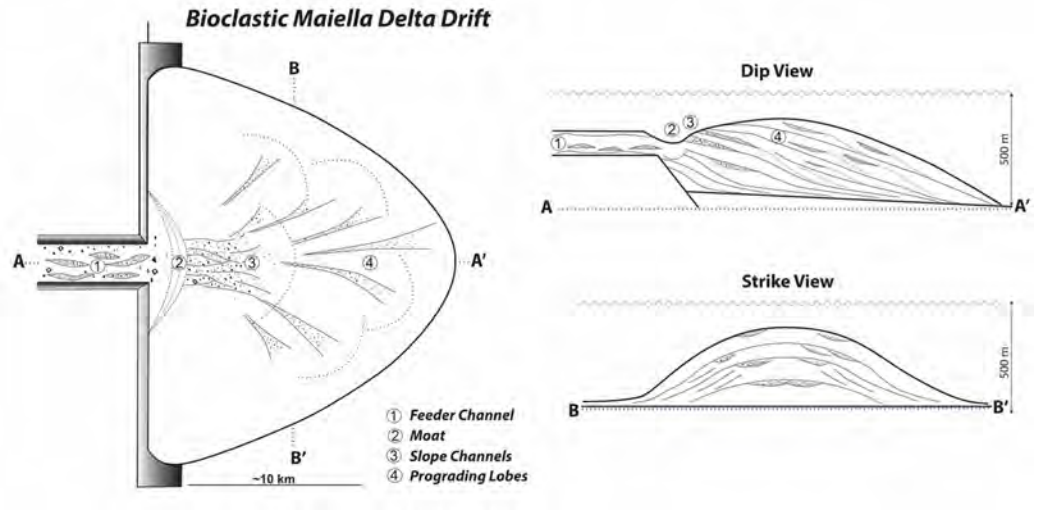

Figure 1: Schematic display of the Maiella drift delta as plan view and dip and strike cross-sections (from Eberli et al. 2019).

characteristics of highly-concentrated turbidity current deposits. Other elements, like scours filled with pebble- and gravel-sized bio- and lithoclasts and erosive surfaces are typical expressions of transitions from supercritical to subcritical flow (Postma & Cartigny, 2014). Other beds display structures that are associated with hyperpycnal flow.

Hyperpycnal flow is produced when water with higher density - commonly associated with sediment laden river water - flows into a basin. Isolated carbonate platforms, like the Apulian platform was, do not have fluvial transport and thus hyperpycnal flow characteristics must have been produced by another continuous flow, thought to be an ocean current flowing through the feeder channel. The large scale geometry of downlapping coarse-grained lobes as observed in the delta drift are reminiscent of homopycnal jet outflow causing deposition in a Gilbert-type delta (Fig. 2). Thus it is likely that, depending on the sediment load, both flow mechanisms are recorded in the bedsets of the delta drift.

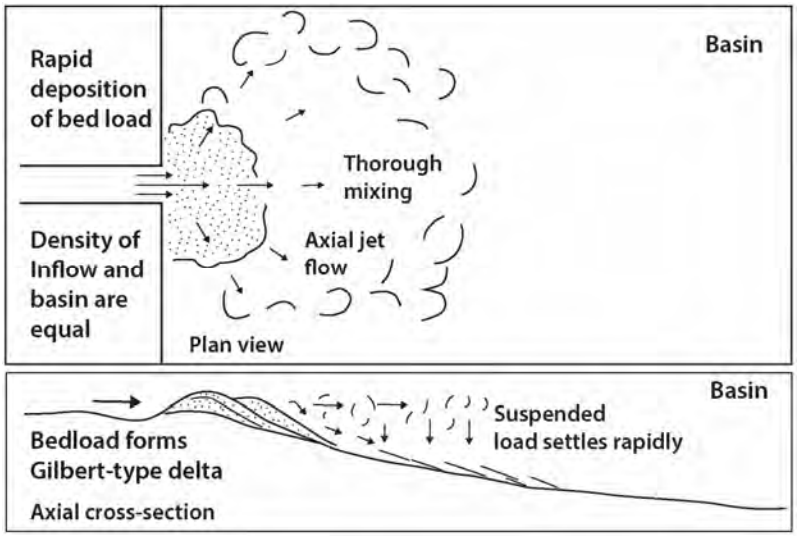

Figure 2: Homopycnal flow model redrawn from Boggs (1987) based on Bates (1953). Homo-pycnal flow leads to rapid deposition of sediment load. The jet outflow causes the formation of Gilbert—type deltas that display topset, foreset and bottomset arrangements of beds.

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. 3). In addition,

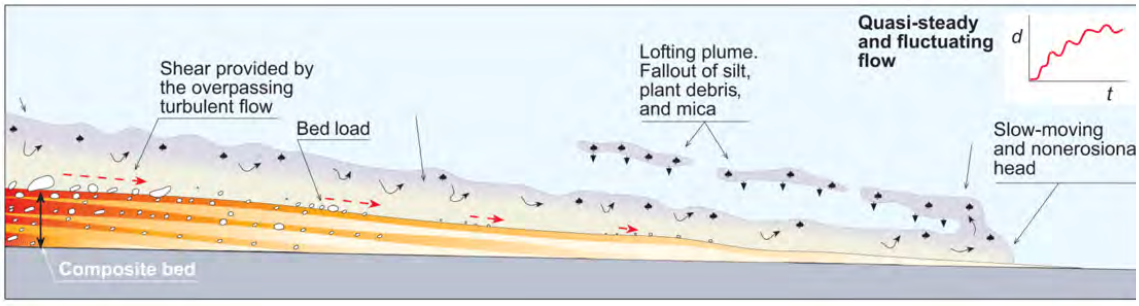

Figure 3: Hyperpycnal flow model Zavala et al. 2011, explaining the coarse-grained composite beds produced by the shear of an overpassing hyperpycnal flow with fluctuating strength. We will test if quasi-steady ocean currents with fluctuating strength results in a similar depositional pattern.

hydraulic jumps caused by the topography are thought to produce transitions from subcritical to supercritical flow and several of the observed sedimentary features.

A second major objective of the project is to use the clast distribution of the delta drift to interpret the depositional process in the more distal portion of the delta drift. The combination of 3D GPR, flattening and thick slice visualization has provided an unprecedented view of sedimentary structures inside the grainstone beds of the Madonna della Mazza quarry (Grasmueck et al., 2019). The random distribution of the clasts indicates a freezing of the dense hyperpycnal flows (Fig. 4). This year we plan to improve the visualization of the clasts in each layer to precisely assess the clasts in various layers.

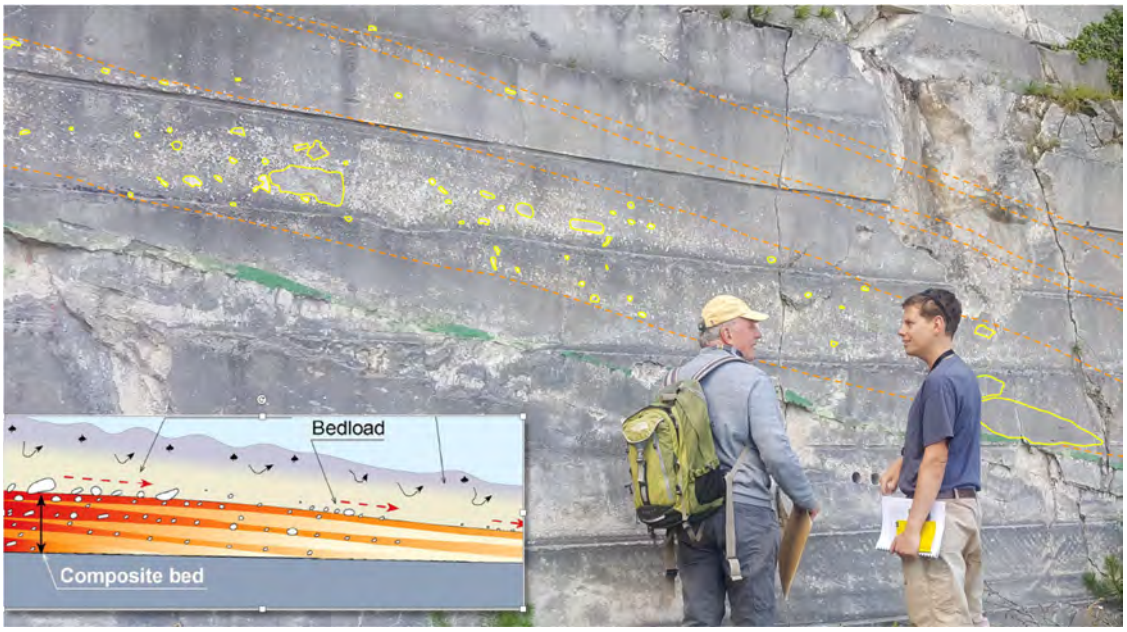

Figure 4: Clast distribution in the strata of the Madonna dell Mazza quarry. Clast appear as white specks in the quarry floor and walls; larger clasts are outlined in yellow. Inset is schematic display of the clasts deposited by hyperpycnal flow (Zavala et al., 2011).

APPROACH FOR VISUALIZATION OF CLASTS

To be able to visualize and quantify the clasts in individual dipping beds several steps are necessary (Fig. 5). First, a geomodel of the 3D GPR datacube has to be constructed that resolves the individual layers of the quarry succession. The geomodel is then used to flatten each lithoclast bed to obtain a contiguous map view of the bed content. We will use the Pondview (Grasmueck and Viggiano, 2018) thick slice method for the visualization of the clast distribution inside the lithoclast beds. The 2D matrix color rendering of Pondview shows the lateral and vertical clast distribution. The goal is to assess the distribution, size, shape, and orientation of the lithoclasts within each layer. This will support the reinterpretation of the flow- erosion- and transport mechanisms operating during deposition of the drift succession of the Madonna della Mazza quarry.

SIGNIFICANCE

This study will provide for the first time an assessment of the sedimentologic processes of jet flow generated by ocean currents in feeder channels and their depositional products. We suspect that some deep-water deposits, in particular coarse-grained beds that hitherto have been assigned to gravitational flow mechanisms, might be better explained within the context of a deep-water delta. The geometry and facies of this thick coarse-grained in contourite drift type points towards a new depositional model in deep-water environments.

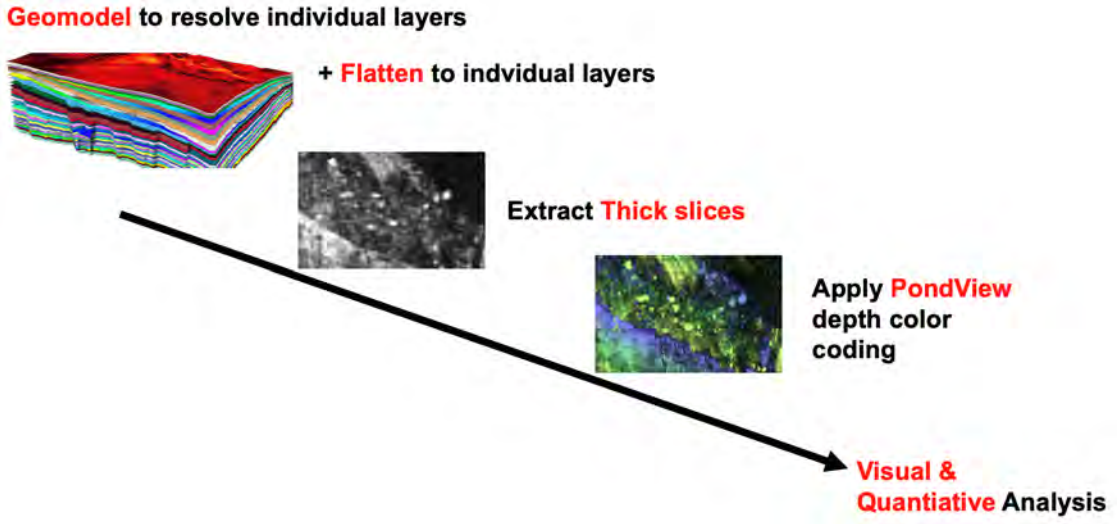

Figure 5: Workflow to visualize and quantify the lithoclast distribution in the Madonna dell Mazza quarry succession of the Maiella delta drift. Geomodel Image from PaleoscanTM interpretation software, Eliis

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Petrophysics

PETROPHYSICAL CHARACTERISTICS OF CARBONATE DRIFT DEPOSITS

Emma L. Giddens, Gregor P. Eberli, and Ralf J. Weger

PROJECT OBJECTIVES

- Define the specific petrophysical characteristics (porosity, velocity, resistivity and permeability) in plugs and logs of carbonate contourite drifts using data from drifts in the Maldives, Maiella, Australia, and the Bahamas.
- Contrast the petrophysical properties of drift deposits to those of "other carbonates", representing various depositional environments, lithology and composition.
- Investigate the pore structure of fine-grained carbonate drift deposits in search of an explanation for their high resistivity.

PROJECT RATIONALE

Last year we analyzed the petrophysical properties of the Miocene drift deposits in the Maldives and Cretaceous drift strata in the Maiella, both of which represent delta drifts - a newly discovered specific carbonate contourite drift type (Lüdmann et al., 2018; Eberli et al., 2019). These delta drifts are built by prograding lobes, which are typically coarse-grained in their proximal part and finer grained in the distal fringes. In our data set, samples from the Maldives are from fine-grained intervals, while the samples from the Maiella represent the coarse-grained facies of the delta drift.

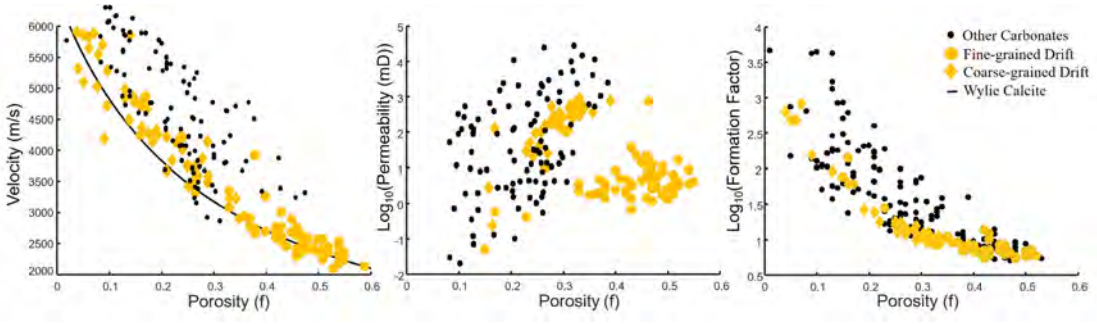

Figure 1: Petrophysical properties of carbonate delta drift deposits (yellow symbols) compared to "other carbonates" from the CSL data base (black dots). Left: Velocity-Porosity plot of drift deposits displaying the small variation exhibited by drift carbonates compared to other carbonates. Middle: Porosity-Permeability plot of drift deposits displaying the separation of coarse and fine-grained deposits. Right: Porosity-Formation Factor (resistivity) plot of drift deposits and 'other carbonates'.

Some characteristics of these two carbonate delta drift deposits are: a) the very high porosity of the coarse-grained facies, which in plugs reaches up to 59%; b) compared to other carbonates velocity and resistivity vary less at any given porosity, and c) permeability separates into two populations according to the grain size (Fig. 1).

This year we will expand the petrophysical investigation to other contourite drifts by analyzing samples from large, separated drift deposits collected during ODP Leg 194 on the Marion Plateau in Australia and the confined drift in the samples cored and logged during ODP Leg 166 in the Bahamas. A plethora of samples of varying age and location are needed for a comprehensive petrophysical description of drift deposits. In addition, we will examine the micropore structure of the fine-grained portion of the drift deposits which display an unusually high resistivity.

WORKPLAN

Velocity, porosity, resistivity and permeability will be measured on plug samples from drifts on the Marion Plateau in Australia and samples from ODP 166 to the Bahamas. Some of the samples have been measured in earlier studies from the Marion Plateau by Guido Bracco Gartner (unpublished) and by Kenter et al. (2002) from the Santaren drift in the Bahamas. These measurements will be combined with new measurements and added to the petrophysical drift deposit database that already contains measurements from the Maldives and the Maiella. In addition, the texture and mineralogy of each sample will be determined, and the pore type of each sample will be analyzed with digital image analysis following the methodology of Weger et al. (2009). SEM imagery will be used to assess the micropore structure.

Log suites from the three contourite drifts drilled during ODP and IODP expeditions will be used to document the log characteristics of the different drift deposits.

GOAL

The goal of the study is to assemble a comprehensive petrophysical database of carbonate contourite drifts, which have the potential to be either underexplored carbonate reservoirs or seals in the petroleum system.

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CALIBRATING ACOUSTICAL AND ELECTRICAL PROPERTIES TO TOC DISTRIBUTION IN THE VACA MUERTA FORMATION, NEUQUÉN BASIN, ARGENTINA

Ralf J. Weger, Max Tenaglia, Leticia Rodriguez Blanco, Peter K. Swart, and Gregor P. Eberli

PROJECT OBJECTIVES

- Calibration of acoustical and electrical properties to TOC measurements on plug samples from the Vaca Muerta Formation.
- Document resistivity anisotropy observed in mixed carbonate-siliciclastic plug samples from the Vaca Muerta Formation.
- Determine the potential variability of TOC values derived with the ΔlogR method using horizontal v.s. vertical plugs (e.g. logs from vertical v.s. horizontal wells).

PROJECT RATIONALE

Successful exploitation of unconventional reservoirs requires the reservoir zones to be brittle, porous, and rich in organic carbon. Modeling results have shown that increasing porosity, clay content, and both kerogen and organic carbon content will decrease a rock's brittleness. Porosity and clay content can be determined from neutron and sonic measurements, allowing characterization of a formation's ductile and brittle behavior, but the properties and proportions of Kerogen and/or TOC are often more difficult to determine. One frequently used, fast, inexpensive and convenient method for Total Organic Carbon (TOC) content determination is the ΔlogR method (Passey et al., 1990) and its various revisions and improvements. This method has been applied successfully in conventional source rock evaluation for decades but is being used in unconventional plays more and more frequently. However, results derived using the ΔlogR method depend on boundary values established from existing velocity and resistivity measurements. Both boundary values and measurements (both velocity and resistivity) are highly sensitive to variations caused by anisotropy, and the degree of acoustic and electrical anisotropy is often poorly documented.

DATA SETS

Here we use electrical and acoustic properties of over 250 Vaca Muerta plug samples previously analyzed for acoustic velocity (Fig. 1). Samples were

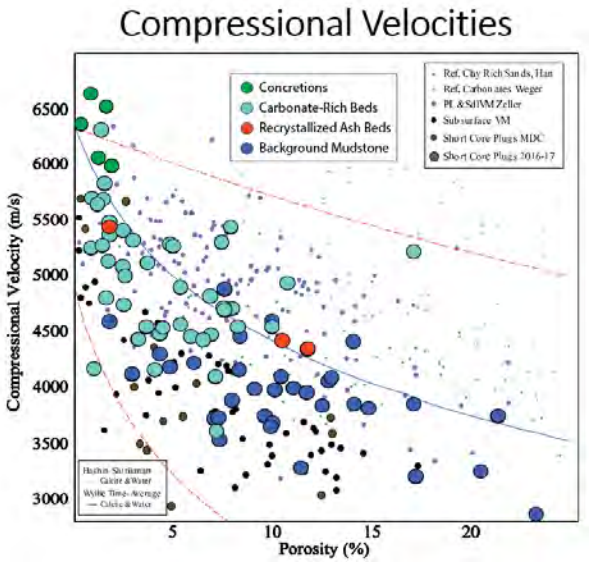

Figure 1: Compressional p-wave velocities of 250 Vaca Muerta plug samples.

derived from both outcrop and subsurface. Over 100 short cores were drilled in outcrops covering proximal to distal locations; subsurface plugs are from the El Trapial block (Weger et al., 2018).

APPROACH AND WORKFLOW

Plugs were cut in pairs or triplets at almost identical depth to determine acoustic and electrical anisotropy (Fig. 2). The method is described in more detail by Weger et al., (2016). Carbonate content was determined by crushing part of the sample and dissolving the carbonate portion using 10% hydrochloric acid. The TOC content was measured on the remaining insoluble material using an elemental analyzer. Acoustic and electrical data of mudstone samples from the Vaca Muerta Formation are compared to both geochemically derived TOC content and gamma ray measurements to provide a quantitative calibration of the TOC values derived from acoustic, electrical, and/or gamma ray measurements to geochemically measured TOC content. In particular, the availability of plug pairs (and triplets at orientation) will allow us to quantify the variations in TOC values derived with Passey's ΔlogR method if strong acoustical and electrical anisotropy exists.

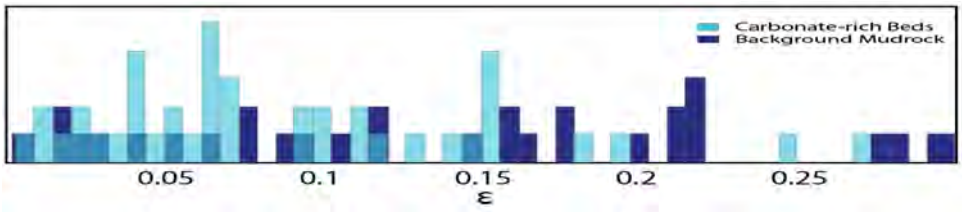

Figure 2: Velocity anisotropy parameters "ε" displaying large differences between horizontal and vertical measurements in Vaca Muerta mudstones, but very little differences in the more carbonate-rich beds of the Vaca Muerta Formation.

SIGNIFICANCE

Estimates of TOC based on spectral gamma ray provide a qualitative indication of overall organic richness but they are not precise enough to provide a reliable method to determine TOC values. The ΔlogR method on the other hand, provides a means of estimating TOC reliably in a variety of different settings and scales. The strong correlation between ΔlogR derived estimates from plugs samples and direct chemical measurements will provide the basis for reliable subsurface application in the Neuquén Basin.

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Unconventional Reservoirs

ENHANCED OUTCROP TO THE 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 in thin sections and cuttings from 20 wells and outcrop sections across the basin.
- Evaluate the similarities and differences of compositional variations 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

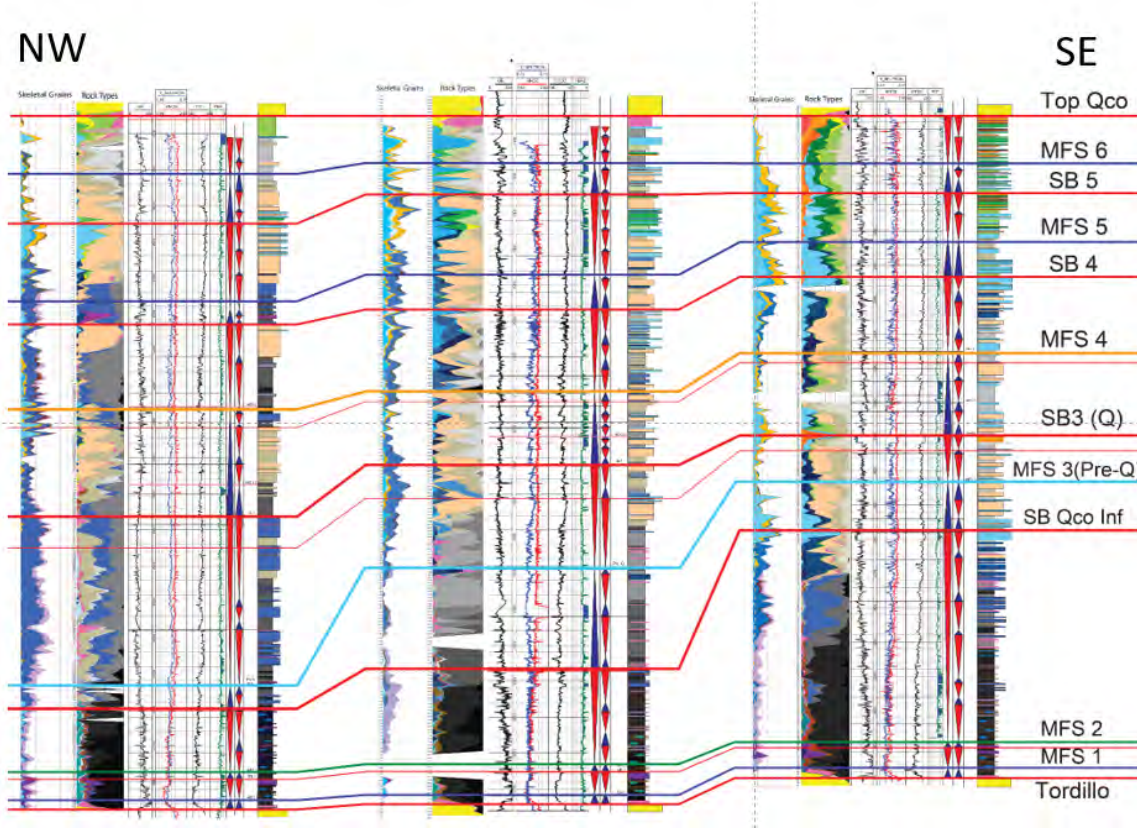

Figure 1: Correlation of cycles and sequences between three wells using cuttings and cores together with log information. The quantification of the composition adds valuable information about the lateral and vertical changes of facies.

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 (0.5-1 m 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 takes into account 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 sedimentological variations that are created by the cyclic deposition. In addition, it reflects the proximal distal facies changes as well as changes through time.

APPROACH

The study can rely on a large data set from the subsurface produced by Taury Smith which will be compared to the outcrop sections. The data set consists of a cutting 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 wells he studied are within 10 km of the outcrop belt.

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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VARIABILITY WITHIN A TARGET ZONE ANALOG OF THE VACA MUERTA FORMATION, ARGENTINA

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

PROJECT OBJECTIVES

- Evaluate lateral heterogeneities of potential landing zones.
- Document the lateral variability along 2 km of outcrop in TOC-rich intervals as analogs for variability encountered during horizontal drilling.
- Illustrate heterogeneity using regularly-spaced, short (20-30 m) vertical sections along a scan line.

PROJECT RATIONALE

Over the last seven years, the CSL has assembled a comprehensive set of reference data from the Vaca Muerta Formation in the Neuquén Basin (Eberli et al., 2017). The dataset comprises over 30 detailed lithologic sections in proximal to distal positions, covering the majority of the basin. The lithologic sections contain meter spaced gamma ray data and over 4000 samples that have been collected at these gamma ray locations. The samples are analyzed for Total Organic Carbon (TOC), carbonate content, and $\delta^{13}C$ (both org and inorg). Over a hundred 1m short cores were recovered from the Vaca Muerta Formation, targeting the dominant facies present in the outcrops of the Sierra de la Vaca Muerta and the Puerta Curaco area.

In the Puerta Curaco area alone we constructed a formidable framework for the comprehensive assessment of the sedimentological, stratigraphic and petrophysical variability by comparing sections separated by block scale distances of several kilometers (Weger et al., 2017). Although these data provide a good estimate of variability within a block, they do not capture the variability along an individual horizontal well. Yet, the productivity of horizontal or deviated non-conventional wells is significantly impacted by lateral reservoir heterogeneity. Several semi-analytical tools such a technique based on Green's functions called the s-k*method are capable of modeling these heterogeneities (Wolfsteiner et al., 2000). In this project, we propose an outcrop based approach to assess the lateral variability within individual target intervals by measuring several short sections separated by only 10's or 100's of meters along TOC-rich intervals.

APPROACH AND WORKFLOW

We will collect a series of short (25-50m) lithologic sections along a scan line between previously measured long sections (e.g. Fig. 1). These series of short sections will be placed in high TOC intervals that represent outcrop analogs of subsurface landing zones that would represent potential targets for horizontal wells. Each section will be covered by meter spaced gamma ray measurements and geochemical samples. Along the scan line (a high TOC bed) we will collect the same data (gamma ray, TOC, carbonate content, and $\delta^{13}C$), at 5 – 10 m intervals. The first target area is at Puerta Curaco, Aguada de los Tamariscos, Yesera del Tromen, and Pampa Tril where we measured 13 different sections

with a total length of over 2000 m. Now we will return to several of the High TOC intervals in the above mentioned lithologic sections and measure additional detailed lithologic sections with varying lateral offset (50-500 m).

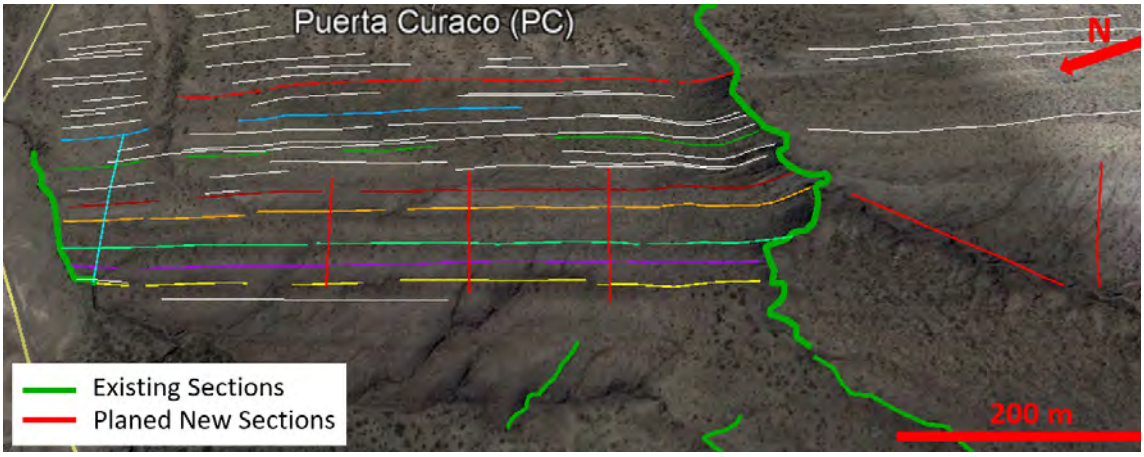

Figure 1: Proposed new Sections in the Puerta Curaco Area

SIGNIFICANCE

The lithologic sections are likely to display many similarities, but will highlight the differences in carbonate and organic content. They will provide the basis for a detailed quantification of the lateral variability that exists along a potential horizontal well path. This quantification of observed lateral heterogeneities will be beneficial in optimizing landing zone approach and designing productive non-conventional well paths in high TOC intervals of the Vaca Muerta Formation.

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Geobiology and Geochemistry

MICROBIAL MEDIATION ON EARLY CEMENTATION PROCESSES

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

PROJECT OBJECTIVES

- To elucidate whether initial stabilization and cementation of carbonate grains are mediated by microbial interactions of indigenous microbial communities.
- To study whether EPS exudates play an imminent role in the early stages of sediment stabilization and cementation by cohering sediment particles and providing a template for nucleation to occur.
- To identify textural forms and mineral microstructure composition of early marine cementation areas using petrographic thin-sections, SEM-EDS and X-Ray diffraction analyses.

PROJECT RATIONALE

A growing number of studies suggest that cementation is not a strictly inorganic process as microbial binding in micritic bridging and fringing cements have strengthened the notion regarding the involvement of microbes in initial cementation and stabilization of sediments (Dravis, 1979; Hillgärtner et al., 2001). These observations are further supported by our preliminary experiments that use in-vitro incubations of ooids in the presence and absence of indigenous microbial populations (Fig. 1). Based on the growing evidence supporting the biological mediation theory, this study aims to evaluate whether first cements in marine ooid grains are largely the result of microbial binding and/or microbially induced precipitation.

APPROACH

To assess the impact of microbial precipitation in early cementation processes experiments will be undertaken using incubation chambers containing freshly collected ooids from an area of active ooid formation on Schooners Cay (Bahamas). Two cohorts of treated and untreated groups of ooids will be incubated under conditions of no agitation to emulate the quiescent conditions of the flank areas of the shoals. The untreated group represents ooids with their indigenous microbial communities while the treated group comprises sterilized ooids devoid of any microbial influence. The detection of indigenous microbial communities and formation of early precipitates on inter/intragranular contact areas will be monitored at various time intervals (ranging from 0 to 6 months) using SEM and stereo-microscopy. SEM image analysis will reveal the presence and potential involvement of biofilm extracellular polymeric substances (EPS) in carbonate precipitation at grain-to-grain contacts and non-contact areas of the grains. Given that EPS matrix can act as a template for carbonate mineralization via the formation of amorphous calcium carbonate (ACC), we will explore whether ACC nanograins can intervene in the initial process of cementation of ooids. ACC will be detected with morphological attributes based on the SEM image analysis.

Textural forms and mineral microstructure compositions of early marine cements will be analyzed using petrographic thin-sections, SEM-EDS and X-Ray diffraction analyses.

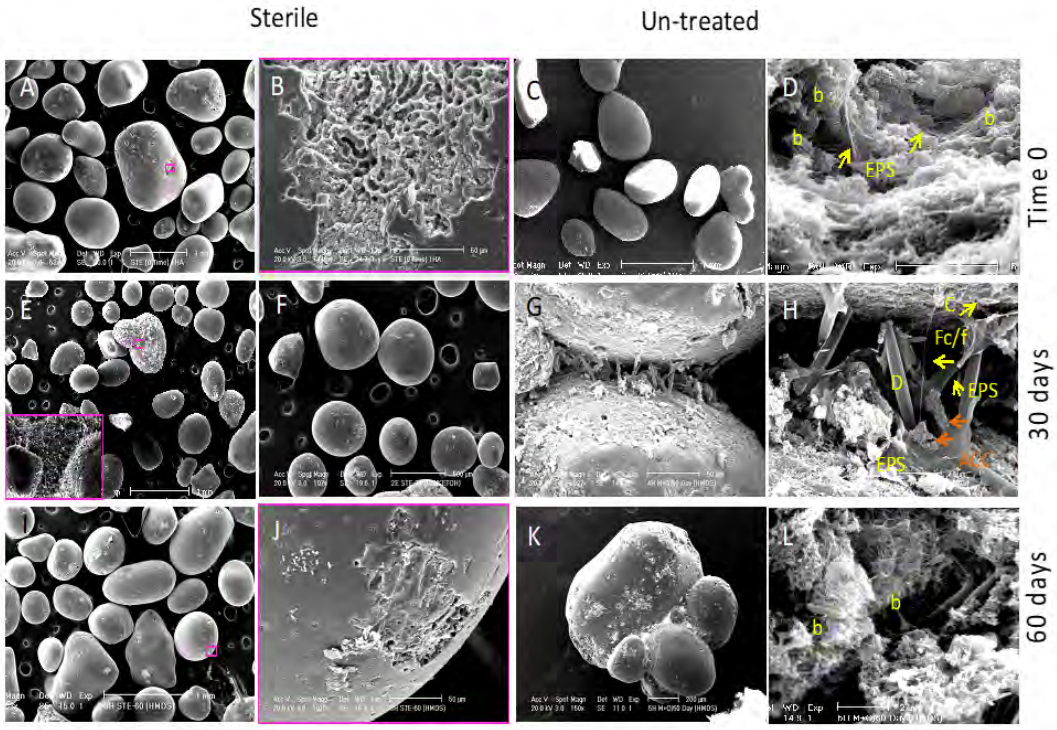

Figure 1. Incubation Experiments. A) Sterilized ooids from Schooner Cay denoting an admixture of polished and bored ooids at time=0; B) Higher magnification image of panel A showing micritization at the periphery of the ooid cortex; C) Well-sorted and polished ooids at time=0, (untreated samples); D) Indigenous bacterial (b) flora and organic mucilage (EPS) in a shallow depression of an ooid cortex at time = 0; E-F) Sterilized ooids after 30 days' incubation. Note the unconsolidated nature of the grains. Inset is a heavily micritisized grain at contact area. G) Microbial lodging and EPS at grain contact area of two un-treated ooids after 30 days' incubation; H) Magnification of panel G depicting adjacent grains being colonized by EPS, diatoms (d), coccolithophore (C), filamentous cyanobacteria/fungi (Fc/f) and ACC; I) Sterilized ooids after 60 days' incubation. Ooids are loosely packed; J) Magnification of panel I showing erosion of the outer cortex and microborings; K) A firm aggregate of grains after 60 days' incubation; L) bacterial colonization in intergranular areas after 60 days.

KEY DELIVERABLES

High-resolution images using SEM will provide insights on the processes that lead to cementation of carbonate grains and biogenicity origins of the precipitated material and preferential location within the rock framework.

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EXPLORING SIGNATURES OF DIAGENESIS USING ROLLING WINDOW REGRESSION

Amanda M. Oehlert and Peter K. Swart

PROJECT OBJECTIVES

- Analyze trace metals and REE concentrations in Clino, San Salvador, and Enewetak cores.
- Examine zones of diagenetic alteration and diagenetic surfaces using Rolling Window Regression Analysis.
- Expand characterization of geochemical signatures unique to specific diagenetic processes in marine carbonates.
- Evaluate impacts of oceanography, sea level, and climate on diagenetic zones.

PROJECT RATIONALE

Recently, Rolling Window Regression (RWR) analysis was demonstrated as a useful tool for characterizing the type of diagenetic alteration a deposit has undergone (Oehlert and Swart, 2019) (Fig. 1). Significant RWR signatures were associated with subaerial exposure surfaces, periods of non-deposition, and the formation of marine hardgrounds (Table 1). However, diagnostic RWR signatures unique to each type of diagenetic process have yet to be characterized.

Therefore, this project has two goals: 1) to determine if these RWR signatures are applicable to other shallow marine settings by applying the RWR analysis to cores from Enewetak atoll in the Pacific Ocean, and 2) to expand the range of geochemical signatures used in RWR to provide additional constraints in an effort to elucidate diagnostic RWR signatures for each diagenetic process.

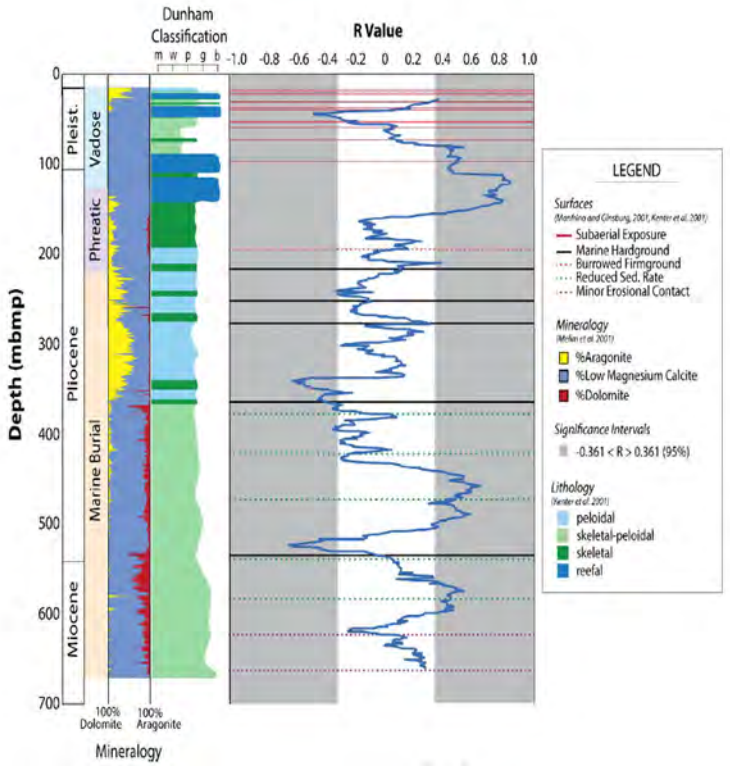

Figure 1: Rolling window regression analysis (30 m window) from the Clino core. From Oehlert and Swart, 2019.

APPROACH

In order to address these goals, we will analyze the stable isotope composition and trace element concentrations of a core from the Enewetak atoll, the trace element concentrations of sediments at Clino and San Salvador, and incorporate published records of stable isotopes (Melim et al., 2001; Dawans and Swart, 1988) to provide high resolution geochemical records for RWR analysis. Then, a systematic evaluation of diagenetic alteration in both the Atlantic Ocean and Pacific Ocean will be conducted to determine if diagnostic RWR signatures can be developed for unique diagenetic processes.

Table 1. Hypothetical relationships between stable carbon and oxygen isotope shifts in marine carbonates from Clino, their RWR correlation coefficients, sedimentological and diagenetic processes and their interpretation in the geological record.

Interpretation	Sedimentology	Diagenesis	RWR correlation	$\delta^{13}C$ shift	$\delta^{18}O$ shift
Marine hardground		Sulphate reduction	Negative	−	+
Marine hardground		Marine cementation	Positive	+	+
Subaerial exposure		FW diagenesis	Positive	−	−
Subaerial exposure		FW diagenesis	Negative	−	+
Aggradation/low stand	Facies change		Positive	−	−
Progradation	Facies change		Positive	+	+

SIGNIFICANCE

RWR analysis of geochemical records from carbonate sediments will be a powerful tool in understanding diagenesis in marine carbonates if diagnostic RWR signatures can be developed for each diagenetic process (*ie* short-term subaerial exposure vs long-term subaerial exposure).

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CENOZOIC EXPRESSION OF ROLLING WINDOW REGRESSION IN MARINE CARBONATES AROUND THE GLOBE

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

PROJECT OBJECTIVES

- Evaluate RWR trends in geochemical parameters (stable isotopes, trace elements) from:
  - Shallow marine environments
    - Clino, Unda, Enewetak, San Salvador.
  - Periplatform settings
    - Great and Little Bahama Banks, Maldives.
  - Pelagic Environments
    - Walvis Ridge, Nicaraguan Rise, Queensland Plateau, Madingley Rise.
- Assess the utility of RWR in chemostratigraphic correlations, biogeochemical cycling, and reconstruction of diagenetic events in a range of Cenozoic depositional environments.

PROJECT RATIONALE

Rolling window regression (RWR) analysis has recently been shown to be a useful tool in identifying the types of diagenetic processes that affect stable isotope records ($\delta^{13}C$ and $\delta^{18}O$ values) in shallow marine carbonates (Oehlert and Swart, 2019). Statistically significant and unique trends in RWR analysis were observed in relation to subaerial exposure, the development of marine hardgrounds, and periods of reduced sedimentation. Although its utility has been demonstrated in relation to diagenetic events in shallow marine settings, the applicability of RWR to basinal/global chemostratigraphic correlations and major biogeochemical events in Earth history remains untested. Preliminary results from the Nicaraguan Rise (ODP Site 1000) and the Queensland Plateau (ODP Site 811) suggest there may be globally observed patterns in RWR analysis that reflect Cenozoic changes in biogeochemical cycling (Fig. 1). If proven useful, RWR could be another tool to employ when interpreting sedimentological, stratigraphic and diagenetic histories in marine carbonates in the geological record.

APPROACH

We will conduct RWR analysis in 30 m windows on stable isotope and trace element records from cores like Clino, Unda and San Salvador which were collected from shallow marine environments in the Bahamas. RWR analysis in periplatform environments will be tested in cores collected from Great and Little Bahama Bank, and the Maldives. Cores from the Walvis Ridge, Nicaraguan Rise, Queensland Plateau, and the Madingley Rise will be analyzed in order to characterize the pelagic endmember.

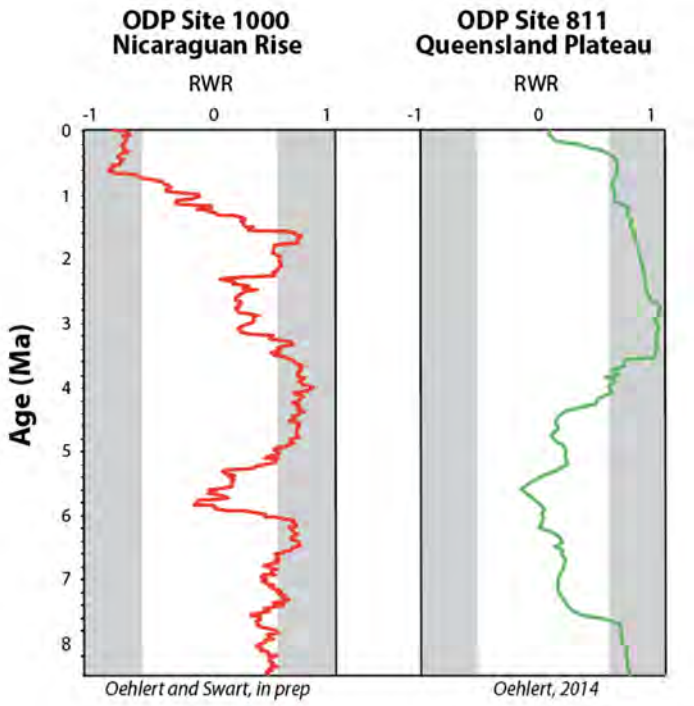

Figure 1: Comparison of 15 m RWR analyses on $\delta^{13}C$ and $\delta^{18}O$ values from pelagic settings at ODP Site 1000 on the Nicaraguan Rise with ODP Site 811 on the Queensland Plateau.

SIGNIFICANCE

Despite differences in sample frequency, both the high resolution RWR record from ODP Site 1000 on the Nicaraguan Rise and the lower resolution RWR record from ODP Site 811 on the Queensland Plateau exhibit similar trends through time, with similar periods of positive RWR relationship, especially over the past 4 million years (Fig. 1). Further investigation is required to identify whether these trends are globally significant by comparing to other pelagic environments. Comparison between shallow and periplatform depositional settings will also aid in the determination of Cenozoic trends in RWR, and whether they can be used to better define sedimentological, stratigraphic, and diagenetic events through time.

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COMPARISON OF ISOTOPIC PATTERNS IN THE PACIFIC AND ATLANTIC: C AND O

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

PROJECT OBJECTIVES

- Determine the role of global sea-level changes in controlling patterns in C and O isotopic composition of bulk carbonates and C isotopic composition of organic material.

PROJECT RATIONALE

While large negative excursions in carbonate and organic carbon $\delta^{13}C$ values during the Neoproterozoic and Paleozoic have been interpreted as records of global carbon cycling (Halverson et al., 2002; Halverson et al., 2010), in some instances these sediments do not record global changes in the Carbon (C) cycle, but rather variations in source and diagenesis. Such interpretations have profound implications for the use of $\delta^{13}C$ values in stratigraphic correlations and for reconstructions of the global C cycle throughout the Earth's history.

Sources of Carbonate: The assumption that $\delta^{13}C$ values record the composition of the global pool of dissolved inorganic C was tested by examining the $\delta^{13}C$ values of sedimentological sequences recovered from a transect of cores drilled off a modern carbonate platform in the Bahamas (Great Bahama Bank) which had been independently dated (Swart and Eberli, 2005). This study revealed that while the $\delta^{13}C$ values of the sequences were similar, and therefore could be used for stratigraphic correlation, the $\delta^{13}C$ values were not related to the global record of $\delta^{13}C$ values found in the shells of planktonic organisms. Rather the variations were related to sea-level controlled input of carbonate with distinct $\delta^{13}C$ values originating from adjacent platforms. Evidence from other Modern platforms such as in The Maldives, The Great Barrier Reef, and The Great Australian Bight show that this process is global (Swart, 2008).

Sources of Organic Material: One of the key pieces of evidence which has been used to support the original nature of the carbonate $\delta^{13}C$ values is the covariance of $\delta^{13}C$ values in the carbonate and organic carbon in the same deposit. However, it has been shown in a study of carbonates deposited over the past 5 myrs adjacent to Great Bahama Bank that varying correlations ($\sim +1$ and 0) between the $\delta^{13}C$ values of organic and inorganic carbon can be the result of different degrees of mixing between materials derived from different sources (Oehlert et al., 2012). In fact, the strongest correlations arise in situations where there is mixing between two sources with distinctive $\delta^{13}C$ values. Such variations are unrelated to changes in the global carbon cycle. Similar patterns have been found at locations adjacent to other modern carbonate platforms.

Diagenesis: It is well known that during the Pleistocene global sea-level fell numerous times subjecting shallow-water carbonates to meteoric influence

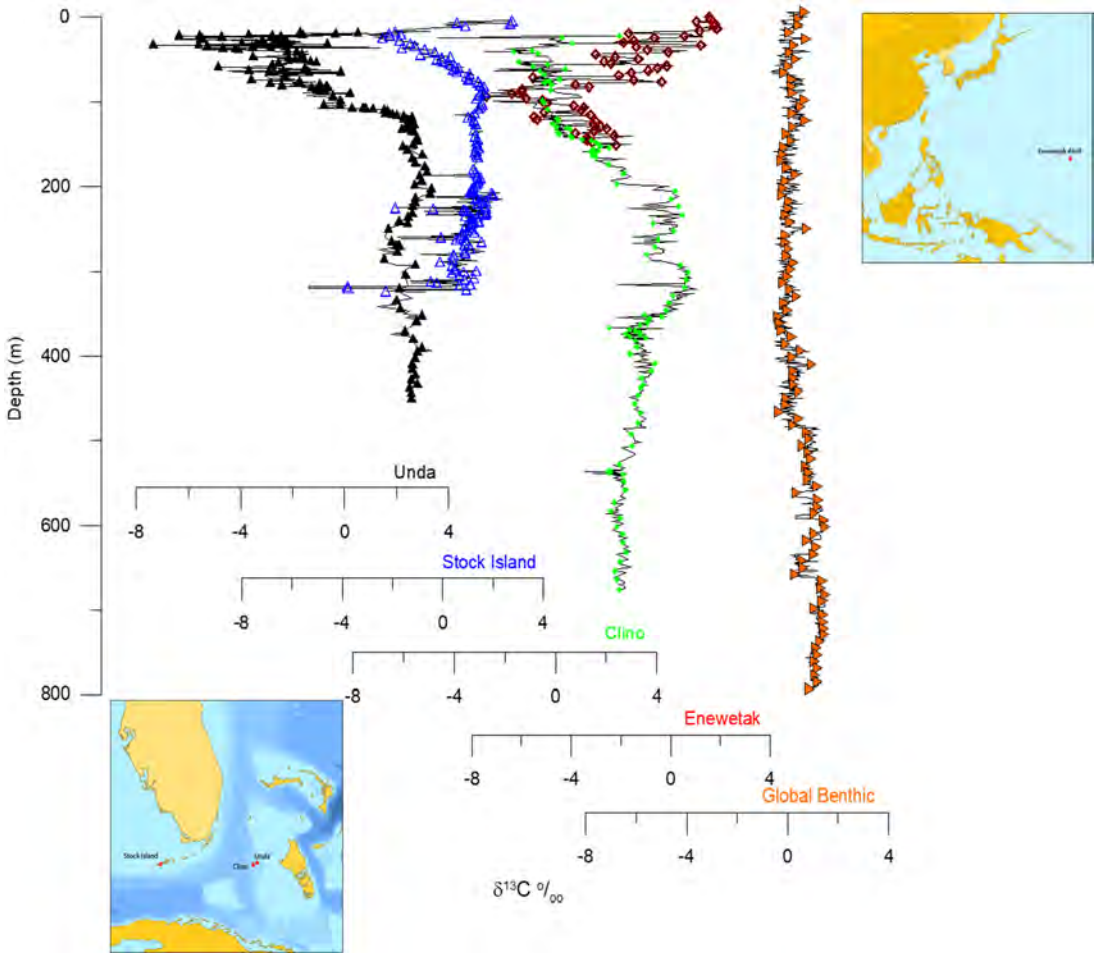

Figure 1: Comparison of the record of $\delta^{13}C$ values from locations in the Atlantic (Unda, Stock Island, and Clino) with the Enewetak record of Quinn (1991) and the global benthic record (Zachos et al., 2001). Data from Unda, Clino are from Melim et al. (2001) and from Stock Island from Melim et al. (2004).

and impacting the $\delta^{13}C$ values of the carbonates. Changes of similar magnitude and over equivalent depth intervals have been documented during time periods such as the Neoproterozoic, but in these cases the changes have been interpreted to be original (Hoffman et al., 1998). One of the prime pieces of evidence, cited by many workers, supporting the original nature of the changes in $\delta^{13}C$ values is that the changes in the Neoproterozoic are global in nature and therefore could not be a result of local diagenesis. However, global sea-level changes will influence sediments in all localities in the same manner and therefore the Pleistocene in the Bahamas should look very similar to a Pacific atoll, such as Enewetak.

SCOPE OF WORK

We have already carried out several studies of the variation of $\delta^{13}C$ and $\delta^{18}O$ values on the cores from the Bahamas (Clino and Unda) (Melim et al., 2001; Oehlert and Swart, 2019; Swart and Oehlert, 2019) and compared the $\delta^{13}C$ values with published data from Enewetak (Quinn, 1991) and the global

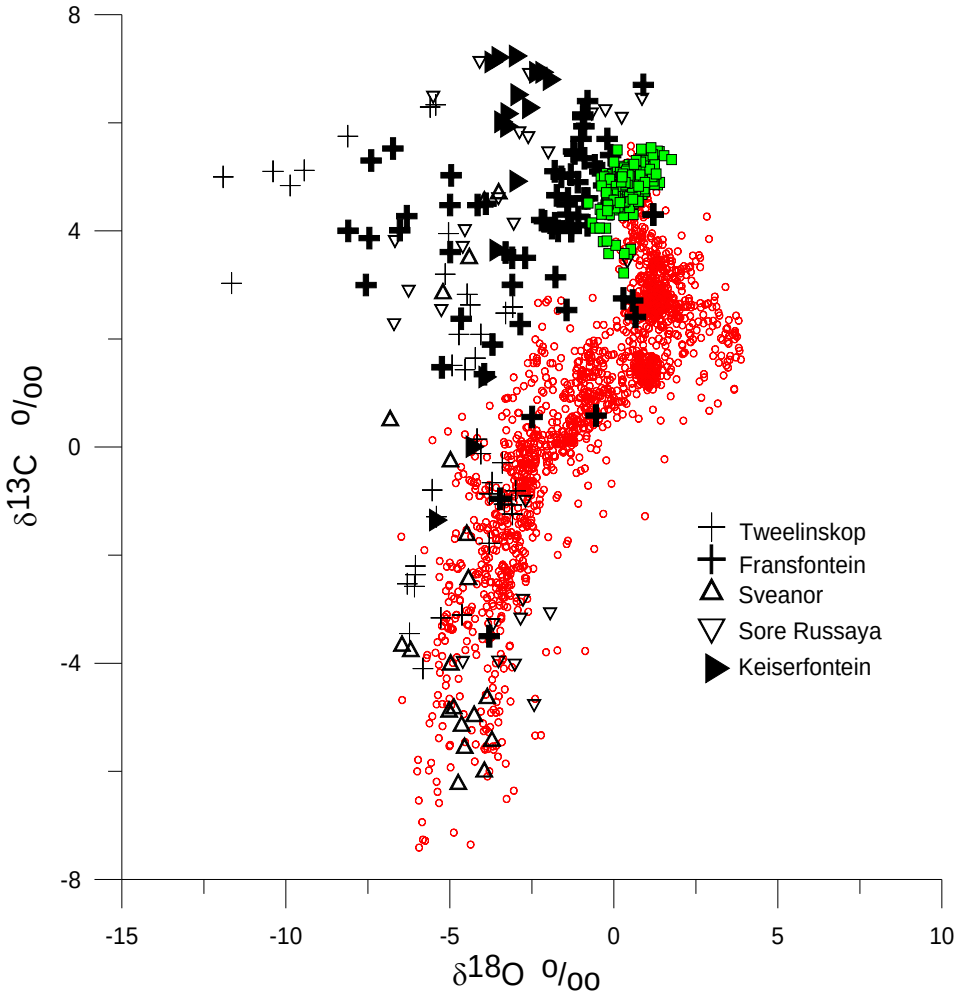

Figure 2: Variations in the $\delta^{13}C$ and $\delta^{18}O$ values from Clino (red) (Melim et al., 2001) and Modern surface sediments (green) (Swart et al., 2008) compared to variations in Neoproterozoic carbonates associated with the Trezona anomaly (Halverson et al., 2002) interpreted to reflect changes in the global carbon cycle. The carbonates from Clino have been clearly diagenetically altered, but fall in the same C and O space as samples which have been interpreted as being original in the Neoproterozoic.

benthic record (Zachos et al., 2001) (Fig. 1). Our conclusion was that similar global variations in the patterns of $\delta^{13}C$ values can occur and are probably related to sea-level changes and the development of meteoric zones of diagenesis in the Pacific and the Atlantic. In order to study these correlations in more detail we have collected a significant amount of new material from the Enewetak cores and are in the process of preparing these samples for XRD and stable isotope analyses. These studies will be carried in conjunction with similar investigations of trace elements variations.

SIGNIFICANCE

These studies will provide a detailed comparison of $\delta^{13}C$ values of carbonate and organic carbon and variations in $\delta^{18}O$ values between two sites known to have been influenced by a global change in sea level. Key questions which will

be answered deal with the extent that global changes in $\delta^{13}C$ values can be caused by global scale diagenetic events induced by sea-level variations and whether such process are responsible for the variations in $\delta^{13}C$ and $\delta^{18}O$ values observed in Neoproterozoic rocks (Fig. 2).

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COMPARISON OF ISOTOPIC PATTERNS IN THE PACIFIC AND ATLANTIC: S, Δ_{47}, AND B

Evan Moore and Peter K. Swart

PROJECT OBJECTIVES

- Compare changes in S ($\delta^{34}S$), B ($\delta^{11}B$), and clumped isotopes (Δ_{47} and Δ_{48}) in diagenetically altered material from the Atlantic (Bahamas) and the Pacific (Enewetak).

PROJECT RATIONALE

While sulfur ($\delta^{34}S$) and boron ($\delta^{11}B$) isotopes have been used to interpret changes in the oceanic conditions during the Neogene, they have also been used in much older materials extending back into the Proterozoic. For example the $\delta^{34}S$ values of carbonate associated sulfate ($\delta^{34}S_{CAS}$) has been used to interpret changes in the burial of organic material (Lyons et al., 2005) and weathering from continental sources, while $\delta^{11}B$ values have been used as a paleo pH proxy (Kasemann et al., 2010) during snowball earth and other climate events such as those which occurred at the Permo-Triassic boundary (Clarkson et al., 2015). This study investigates the influence of diagenesis on both of these proxies through the examination of their behavior in sediments which have experienced well constrained diagenetic conditions from the Atlantic (Bahamas) and the Pacific (Enewetak). We have already shown that signals comparable to those measured across the Permo-Triassic boundary (Clarkson et al., 2015) and associated with major snowball earth events (Kasemann et al., 2010) can be found within a diagenetically altered shallow marine carbonate (Stewart et al., 2015) (Fig. 1). In addition, we find covarying changes in the $\delta^{34}S_{CAS}$ values within the same sections associated with bacterial sulfate reduction (BSR) coincident with the development of the freshwater lens.

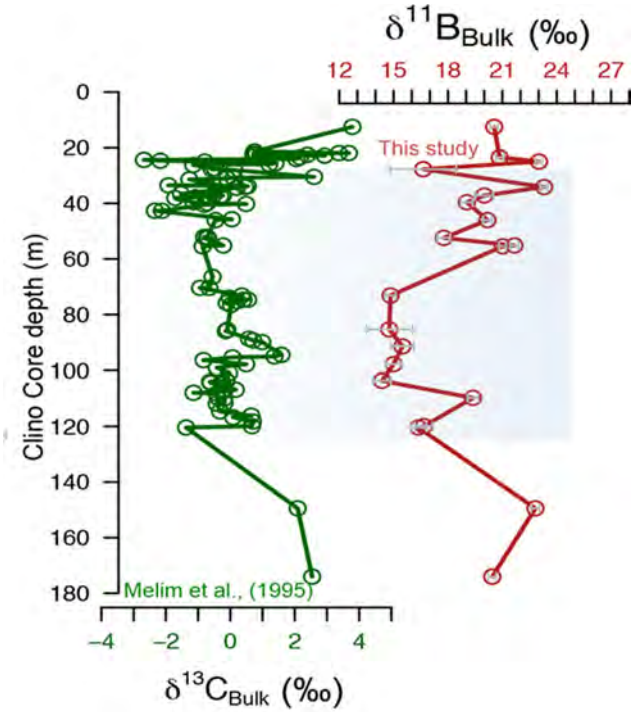

Figure 1: Changes in the $\delta^{11}B$ and co-occurring variations in the $\delta^{13}C$ values of the bulk carbonates from the Clino core taken on Great Bahama Bank. The large change in $\delta^{11}B$ values would be interpreted as reflecting changes in oceanic pH, but in this case is associated with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

SCOPE OF WORK

We will use existing core material from the Bahamas (Ginsburg, 2001) and Enewetak (Quinn, 1991; Wardlaw and Quinn, 1991). Within these samples we will measure changes in the $\delta^{11}B$ and $\delta^{34}SCAS$ values and relate these to changes in sedimentology and petrology changes.

SIGNIFICANCE

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

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TWIN CLUMPED PROXIES AND BEYOND: A NEW CLUMPED ISOTOPE PROXY, Δ_{48}

Peter K. Swart and Chaojin Lu

PROJECT OBJECTIVES

- To determine the rates of change in the Δ_{48} value in carbonate minerals relative to changes in the Δ_{48} value during heating and cooling for the purposes of geospeedometry. This allows the determination of the burial history of carbonate containing rocks.
- Improve the calibration between temperature and Δ_{48} values.

PROJECT RATIONALE

The clumped isotope proxy has caused a revolution in the application of stable oxygen isotopes to carbonate rocks. By examining the difference between the measured and the theoretical 47/44 ratio, the Δ_{47} value can be determined. Calculation of this value eliminates variations in the original C and O isotopic variability of the system and has been shown to be related to temperature in a number of geological systems, both theoretically and experimentally (Ghosh et al., 2006). Since the paper of Ghosh et al. (2006) there have been literally 100s of papers which have not only revised the calibration (Bonifacie et al., 2017; Kelson et al., 2017), but also applied this proxy towards the determination of temperature of carbonate formation (Henkes et al., 2013), the study of diagenesis (Ritter et al., 2015; Staudigel et al., 2018), burial history (Shenton et al., 2015), paleoclimate (Breitenbach et al., 2018),

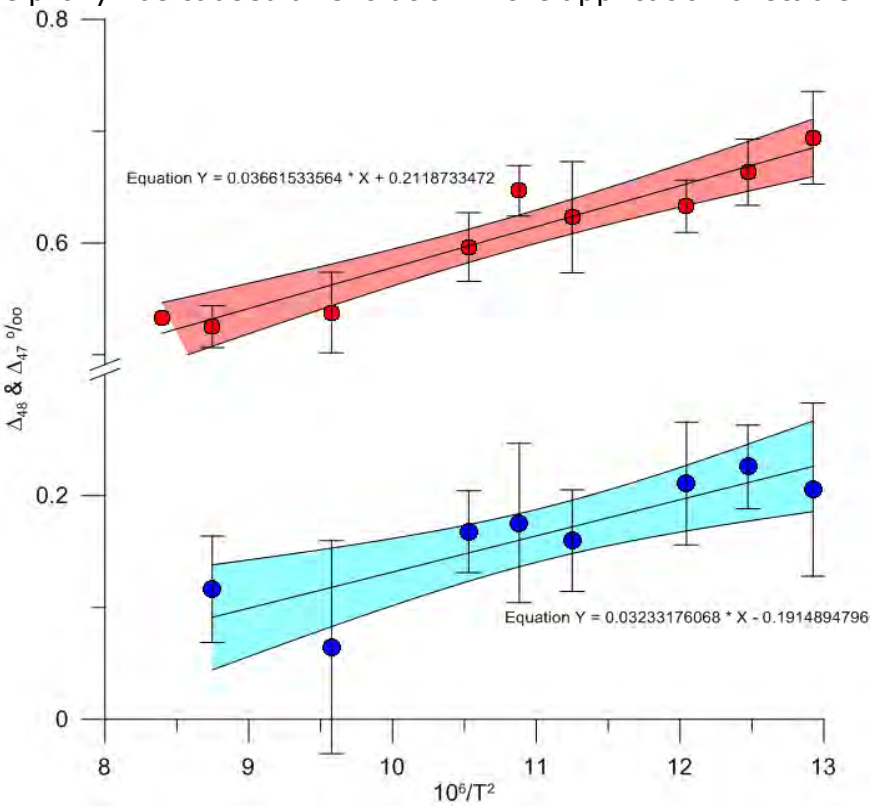

Fig. 1: Comparison of calibration lines for Δ_{47} (red) and Δ_{48} values (blue) using the 253-plus with 95% confidence limits. The equation from the 253-plus is statistically identical to that measured on the 253 (Staudigel et al., 2018).

orogenic uplift (Hough et al., 2014), extraterrestrial geology (Halevy et al., 2011), archaeology (Müller et al., 2017), evolution and physiology of dinosaurs (Eagle et al., 2011) and many other applications.

While studies to date have concentrated on mass 47, there are also clumped isotope species at masses 48 and 49. In the work described here we will continue an attempt to make meaningful clumped isotope measurements on CO_2 at mass 48 ($^{12}C^{18}O^{18}O$ and $^{13}C^{17}O^{18}O$) thus enabling calculation of a Δ_{48} value. The combination of Δ_{47} and Δ_{48} measurements (the 'twin' clumped proxy) have the potential to add a powerful new tool useful in the understanding of equilibrium and non-equilibrium processes, not only during carbonate formation, but also during solid-state reordering. In a first effort we presented a calibration between Δ_{48} values and temperature (Fig. 1) at the 2019 sponsors meeting.

SCOPE OF WORK

Our work will concentrate on two studies.

1. Improve the calibration between Δ_{48} values and temperature, a preliminary version of which is shown in Figure 1.
2. Determine the rates of change of Δ_{48} values (relative to Δ_{47}) which take place during the heating of carbonate minerals.

The Δ_{47} values of carbonates change by solid-state processes when they are heated. The rates of such change have been investigated in low-Mg calcite (LMC), aragonite, and dolomite (Lloyd et al., 2018; Passey and Henkes, 2012; Staudigel and Swart, 2016). Upon cooling the carbonates reequilbrate, but stop doing so once a temperature characteristic of the mineral is attained. This is the so-called blocking temperature. While the different rates of cooling have not been studied, the eventual measured Δ_{47} value may be different than this temperature (usually higher) depending upon the cooling (and heating) history. The blocking temperature for different carbonate mineralogies follows the expected pattern so that dolomite> calcite> aragonite. There have been as yet no studies on high-Mg calcite (HMC) or dolomites with varying stoichiometry, although it might be expected that calcium-rich dolomites would fall between LMC and dolomite and HMC between LMC and aragonite. Our preliminary work, presented at the 2019 sponsors meeting, is summarized in Figure 2. These data suggest that the Δ_{48} proxy changes at faster rates than Δ_{47}. We will verify this by conducting a range of heating experiments on different carbonate minerals at different temperatures.

SIGNIFICANCE

Understanding the history of the Earth's ocean and climate has largely relied on the use of the stable isotopes of C and O in carbonates. The carbon isotopic composition has been widely used to make interpretations about the global carbon cycle while the oxygen isotope composition has been used to ascertain temperature and ice volume. In older sediments it is clear that while the

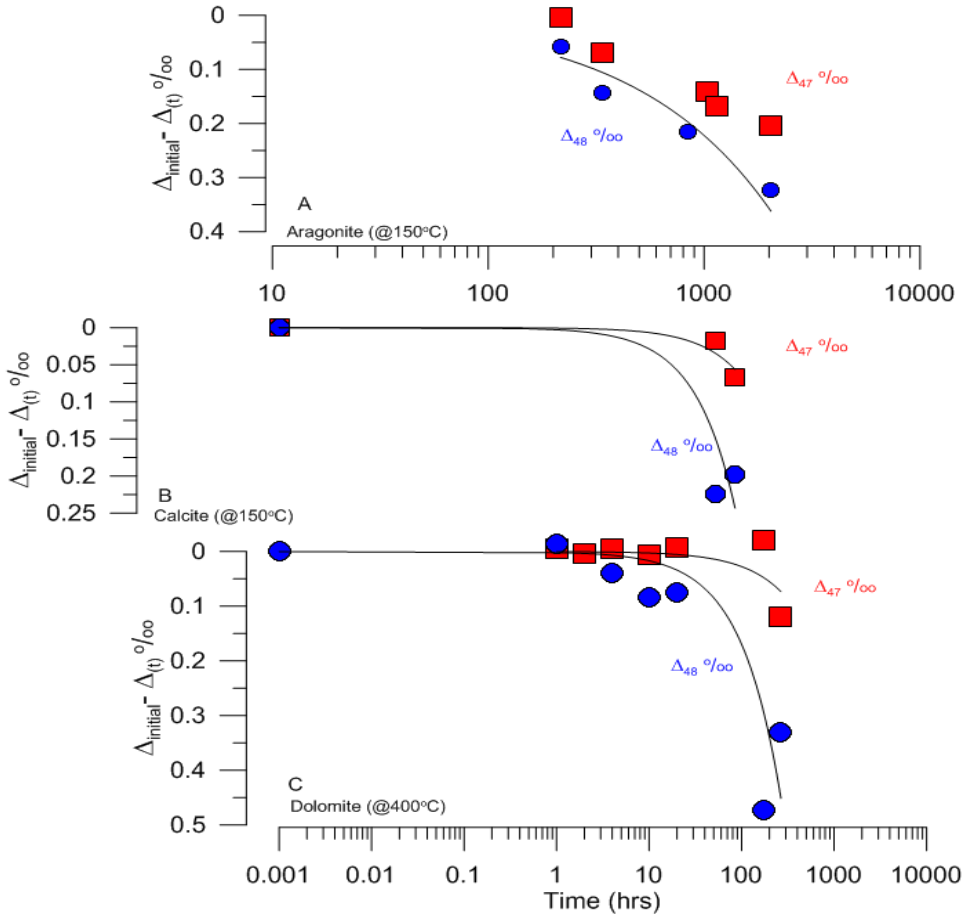

Fig. 2: Preliminary data for changes in aragonite and dolomites for Δ_{47} and Δ_{48} values as a result of heating. Fig. 2A shows changes in values for aragonite as a function of time for samples held at 150°C. Fig 2B: Similar data for LMC at 150°C. Fig. 2C: Similar data for dolomite for sample held at 40O°C. In all cases rate of change of Δ_{48} are faster than Δ_{47}. Overall changes in Δ_{47} values of dolomite are similar to that observed by Lloyd et al. (2018) (at 407°C) even though their experiments were in sealed tubes.

oxygen has been affected by diagenesis, the carbon isotopic composition is retained as alteration takes place in a closed system and unlike oxygen, it is unaffected by temperature. The Δ_{48} value, in combination with the Δ_{47} value, is able to provide additional constraints upon the history of such rocks as the two systems have different blocking temperatures within a single mineral. In situations where there are mixed calcite and dolomite assemblages sophisticated reconstructions of geothermal histories are possible, particularly where there are evolved paragenetic sequences with multiple generations of minerals that can be chemically and physically separated.

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BURIAL HISTORY OF RESERVOIR STRATA USING TWIN CLUMPED ISOTOPES: Δ_{48} AND Δ_{47}

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

PROJECT OBJECTIVES

- Apply clumped isotope methods to diagenetic and 'original' carbonate material from a range of different sedimentary basins in order to ascertain burial history.

PROJECT RATIONALE

Knowledge of the geothermal history of sedimentary basins is vital to understanding the maturation of hydrocarbons. A new approach measures the geothermal history using the clumped isotope method. The deviation, expressed as the Δ_{47} value, is not only known to be dependent on the temperature of formation, but also upon the thermal history (Passey and Henkes, 2012; Shenton et al., 2015). Heating of carbonates during burial breaks existing C-O bonds and there is diffusive migration of C and/or O to new lattice coordinates together with the subsequent reforming of new C-O bonds. This is known as solid-state reordering and tends to drive the Δ_{47} towards a random or stochastic condition. The temperature at which such changes start to take place is known as the blocking temperature and is characteristic of a specific carbonate mineral. Such changes occur without any apparent recrystallization of the sample (i.e. the sample appears unaltered) and without changing the $\delta^{13}C$ and $\delta^{18}O$ value, or other geochemical characteristics. Recently it has been shown that it is also possible to make measurements at mass 48 ($^{12}C^{18}O^{18}O$) and that while the Δ_{48} value behaves in a similar manner to the Δ_{47} value (Fiebig et al., 2019), there are some important differences. One of these is that the rate of solid-state reordering appears to be faster for Δ_{48} when compared to Δ_{47} (Swart et al., 2019).

SCOPE OF WORK

We will make measurements of the Δ_{48} and Δ_{47} in sedimentary basins including the Vaca Muerta Basin (Argentina), Cibao Basin (Dominican Republic), Williston Basin (North America) and Rub'al Khali Basin (Saudi Arabia). A key question at all of these locations will be whether changes in the Δ_{48} and Δ_{47} values of carbonates are a result of recrystallization in fluids with elevated temperatures, or if they reflect solid-state reordering. This question can be answered by examining the Δ_{48} and Δ_{47} of different allochems which exhibit varying degrees of physical evidence of recrystallization. For example, if an originally calcitic fossil, which appears pristine, shows elevated temperatures, this change is likely a result of the blocking temperature having been exceeded during burial. The matrix should also indicate this elevated temperature. If the matrix indicates a different temperature, it is evident that the deposit has experienced a more complex diagenetic and burial history. As

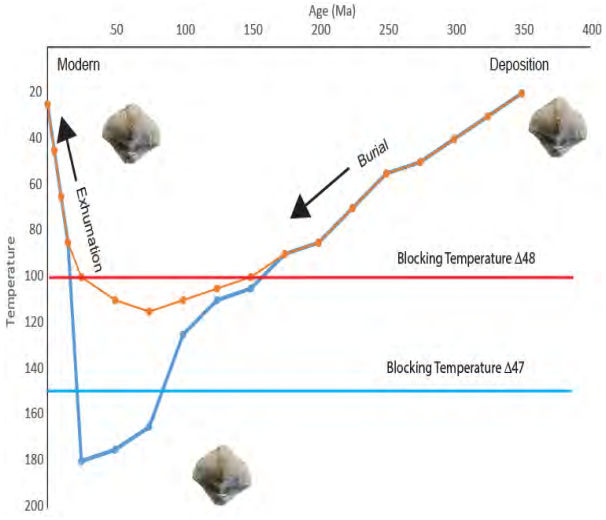

Figure 1: Hypothetical temperature attained during the burial of two basins and the blocking temperatures of Δ_{47} and Δ_{48}.

a result of the observation that Δ_{48} may change more quickly than Δ_{47} when heated and cooled, the Δ_{48} parameter provides additional constraints on the process as well as being able to detect changes below the blocking temperature of Δ_{47}. The difference between the Δ_{48} and Δ_{47} values will be dependent upon the rate of cooling. While rapid cooling will lock in the Δ_{48} and Δ_{47} values at higher temperatures than slow cooling, the rates associated with these processes still need to be determined through laboratory studies. Further information may be obtained in situations where there are mixtures of calcite and dolomite, both of which have differing blocking temperatures (Lloyd et al., 2018; Passey and Henkes, 2012). Two hypothetical cases are presented (Fig. 1). Here two basins have been buried to ~2.5 and 5 km reaching temperatures of ~ 120 and 180°C. If the sample is buried only to 120°C, the Δ_{47} of the calcite will not have been reset. In contrast, the blocking temperature for the Δ_{48} value for calcite will have been exceeded, and therefore a higher temperature will be indicated in material retrieved from the section. In the second case the samples are heated beyond the blocking temperatures. The Δ_{47} values will indicate a higher temperature, while the Δ_{48} will indicate a lower temperature than that conveyed by the Δ_{47}.

SIGNIFICANCE

The twin clumped isotopic proxies can provide new insights into the geothermal and diagenetic evolution of sedimentary basins and will be useful in a range of situations in which traditional methods may not be suitable

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