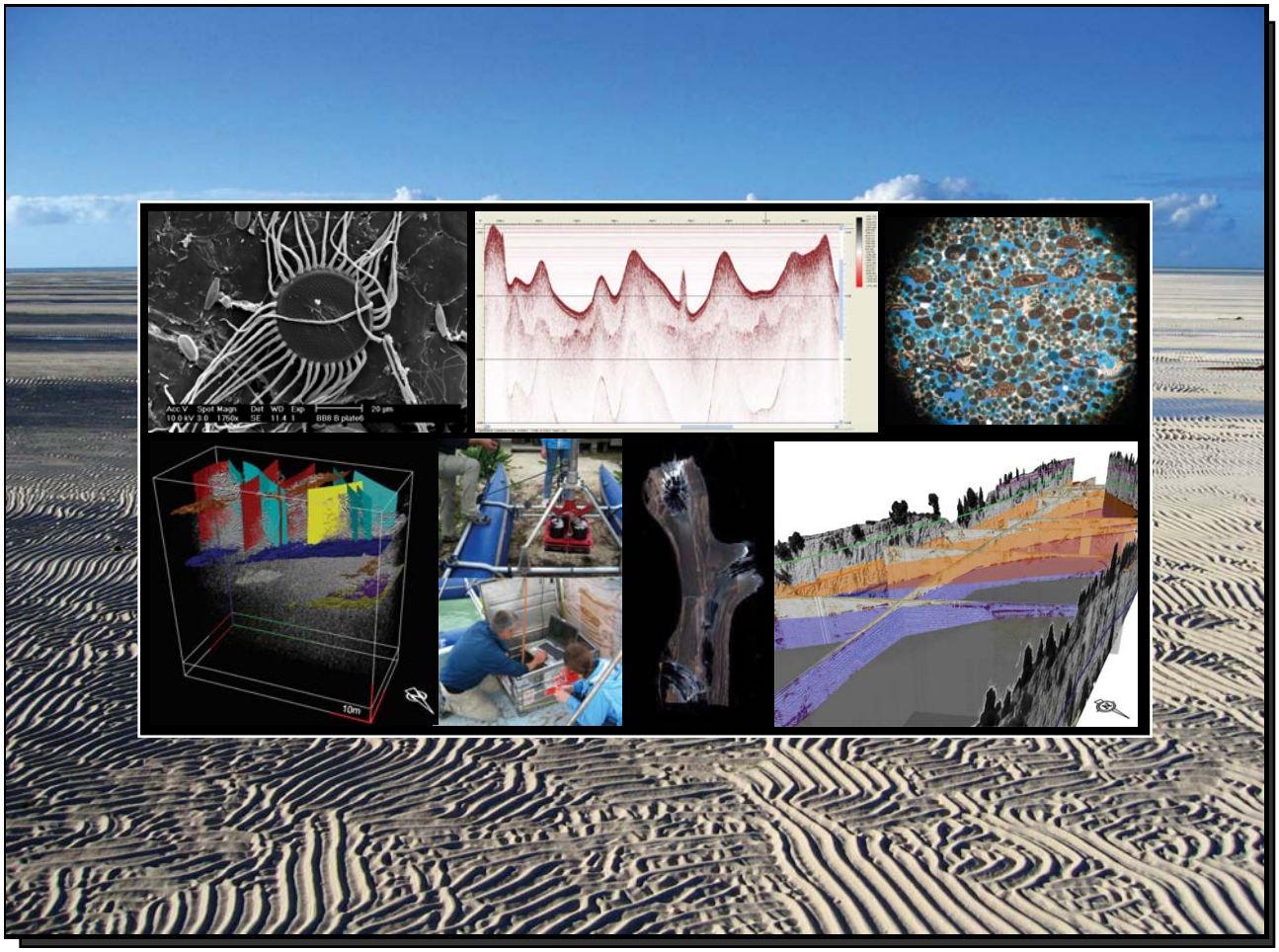
Comparative Sedimentology Laboratory

Rosenstiel School of Marine and Atmospheric Science

University of Miami



2009

Research Program Prospectus

CSL

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Mission of the Comparative Sedimentology Laboratory

The mission of the Comparative Sedimentology Laboratory (CSL) is to conduct multidisciplinary and integrated research in modern and ancient carbonates to enhance prediction of carbonate reservoir attributes on exploration and production scale.

To fulfill this mission we perform fundamental research in geology, geophysics, petrophysics, diagenesis and geochemistry of carbonates by combining observational, laboratory and theoretical studies. In many projects several aspects are applied to reach the research goals. In 2009 these multi-disciplinary studies focus on three depositional environments:

- Shallow-Water Carbonates and Reservoir Characterization
- Deep-Water Carbonates
- Mixed Carbonate-Siliciclastic Systems

These integrated studies and the fundamental projects are described in detail in this prospectus and retrievable on the website www.cslmiami.info

Knowledge Transfer

The Comparative Sedimentology Laboratory transfers the research results to our industry partners through annual meetings, our website, publications and field seminars to ensure the potential implementation of new knowledge in the interpretation and workflow in projects within the participating companies.

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

Field seminars are the best venue to explain and illustrate the processes and products in carbonate geology. In 2009 we offer two field seminars to the Bahamas to our Industrial Associates. The contents and the costs of these seminars are described at the end of the prospectus.

The CSL also offers customized short courses and seminars for the Industrial Associates. Please contact us directly if you are interested in trips to the modern mixed systems of Belize or the outcrops of the Maiella Platform, Italy, the mixed system in the Dominican Republic and the Paradox Basin, or the Madison carbonates in Wyoming.

PERSONNEL

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

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

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

Peter K. Swart, Ph.D. 1980, King's College, University of London, England
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2009 Research Focus

In the 2009 projects we focus on three depositional environments using a variety of techniques and methods with the goal to achieve comprehensive understanding of the sedimentological, geophysical and chemical aspects in each setting. In addition, fundamental research will be carried out in three petrophysical and one geochemical projects.

The **shallow-water carbonates and reservoir characterization projects** aim to understand and document the controlling processes from deposition to stratigraphic product. Studies in the modern address the question of how energy direction and strength influence grain sorting and distribution of reef aprons. One site is located on the Crooked Acklins platform, Bahamas and the other on Glovers Reef in Belize. In both projects, satellite imagery and processing are combined and groundtruthed with surface sediment sampling. These projects aim to refine the conceptual models of the controls on sedimentology of isolated grainy and reef-rich platforms, and implicitly by comparison, of ancient reservoir analogs. In 2009, three projects focus on the vertical facies successions produced by the high-frequency and high-amplitude Pleistocene/Holocene sea level changes. Previous work demonstrated that the re-flooding of platforms after each sea level fall produces a complicated stratigraphic succession that is prone to significant heterogeneity. One study site is the windward margin in the Exumas (Bahamas) where we plan to comprehensively assess the margin stratigraphy and heterogeneity by mapping the modern heterogeneity and coring the parasequence-scale stratigraphy. In a similar approach we investigate the reef dominated Glovers Reef in Belize and the eolian deposits of New Providence Island. These refined studies of high-resolution sequence stratigraphy take advantage of advances in dating techniques that allow recognition of the successive Pleistocene depositional cycles.

Two projects deal with dolomitized strata and focus on the petrophysical characterization of Mesozoic dolomites and the reservoir quality of Ordovician hydrothermal dolomites, respectively. This Ordovician project will focus on the giant Albion-Scipio trend of southern Michigan in which we test the relationship between reservoir quality and the fault zones within the sequence stratigraphic framework. The goal is to increase the predictability of laterally persistent reservoir zones in these systems. The aim of the project in Jurassic and Cretaceous dolomites in the southern Apennine is to evaluate how intrinsic factors affect the acoustic properties in low-porosity dolomites.

A major research effort for 2009 in regards to the reservoir characterization is the investigation of fractures in Cretaceous carbonates. This multi-institutional research effort is a follow-up on the successful acquisition of twelve 3D Ground Penetrating Radar (GPR) data volumes in two quarries imaging fractures in three dimensions at unprecedented resolution to maximum depths between 10 and 30 m. At one study site in the late Barremian strata in Cassis southern France solution-enhanced fractures occur in tight rudist-bearing limestone. There we test how out-crop based methods compare to the sub-surface fracture analysis based on the GPR data. In addition, we address questions in regards to the formation and distribution of the solution enhanced fractures. At the second study site in Maiella Mountains (Italy) we will perform time-lapse Ground Penetrating

Radar (GPR) experiments to detect and quantify fluid flow at the 1-10 m scale for infiltrated water at different time scales. In addition, a flow simulation is planned using the 3D GPR volume as input. Finally the flow simulation and the GPR derived water content change volumes can be compared for an update of the flow simulation model. The results of this multifaceted collaborative research effort will provide new and insightful information of the role of deformation bands on the fluid flow behavior in Cretaceous rudist reservoirs.

The **deep-water carbonate environment** is investigated in six projects. The Petroleum Research Fund provides funding to assess the controls on cold-water coral mound morphology in the Straits of Florida. The goal of the project is a comprehensive assessment of the relationship between mound morphology and environmental conditions at each site. Projects center on the slopes and basinal settings surrounding carbonate platforms. The assessment will include the analysis of: 1) the antecedent topography (investigated on sub-bottom profiler data); 2) coral distribution across the mounds (based on submersible observation and backscatter data); 3) current strength and direction; and 4) temperature and salinity, using stable carbon and oxygen isotopes and trace and minor elements of drilled deep-sea coral skeletons. In addition, temperature and salinity data will be obtained using stable carbon and oxygen isotopes and trace and minor elements of drilled deep-sea coral skeletons. Furthermore, we plan to provide the first petrophysical characterization of deep-water coral mounds of Danian age that are exposed in the Faxe quarry in Denmark. The results are expected to provide a basis for evaluating the reservoir potential of deep-water mounds of this and other ages.

A comprehensive assessment of slope canyons along the southern slope of Little Bahama Bank will quantitatively describe for the first time erosional canyon morphometrics. Ancient slope canyons are exposed in the Maiella Mountains; the completion of a project on the reservoir potential of Cretaceous deep-water redeposited carbonates will complement this study.

An important geochemical aspect of the deep-water environment is addressed in a project funded by the National Science Foundation. This project tests the hypothesis that over the past 10 to 25 Myrs, variations in the $\delta^{13}C$ of marginal platform carbonates are unrelated to changes in the relative burial of organic carbon, but rather relate to global sea-level fluctuations and reflect the relative input of carbonate with high $\delta^{13}C$ values produced in shallow water.

The **mixed carbonate-siliciclastic environment** is the focus of four projects. In the Dominican Republic, the study in the mixed system of the Cibao Basin has been expanded to a) develop an integrated model of fringing reef growth from the Pliocene to Recent including the controlling factors of sea level, tectonics, antecedent topography, and the taxonomy of dominant reef builders and b) document the heterogeneity of reef framework versus matrix sediment and develop an associated porosity model. In addition, we plan to provide a comprehensive digital atlas of the sequence stratigraphy, lithostratigraphy, faunal partitions, petrography, and petrophysics of the Cibao Basin mixed system.

A new initiative in the mixed system of the Nequen Basin (Argentina) has already been started with core description and will continue with an extensive outcrop study with the

goal to develop a predictive model of the prograding Upper Jurassic-Lower Cretaceous mixed carbonate-siliciclastic system in the basin. The project will combine detailed outcrop and subsurface analysis with petrophysical laboratory measurements and state-of-the-art assessment of the pore type geometries to establish a depositional model that captures the spatial variability in depositional and diagenetic rock types, which eventually aids in enhancing the success rate in both the exploration and exploitation in mixed systems.

Four projects are in the category of **fundamental research.** These projects are unrelated to a depositional environment but address various aspects of carbonate petrophysics and geochemistry.

In collaboration with Mark Knackstedt (Australian National University in Canberra, Australia) we image 3D pore network topology and relate the modeled petrophsyical response to laboratory measurements. This year the focus is on documentation of high porosity, high permeability rocks with high acoustic velocity. Such rocks would produce high impedance and would not be considered of reservoir quality. This project aims to explain why these rocks have high stiffness and consequently high velocity. The Vp/Vs-ratio is an important parameter in several geophysical treatises of carbonates, yet in carbonates the Vp/Vs-ratio is highly variable for reasons that are not well understood. A project that employs all the information from the CSL database is designed to address this fundamental problem. Several deeply buried carbonate reservoirs maintain a relatively high porosity. We plan compaction experiments of modern sediments and Pleistocene samples with different amounts of cementation to assess the decrease of the initial porosity and permeability at different burial depth. The results will provide much needed information on the factors that maintain porosity and permeability in the deep burial realm.

The National Science Foundation provides funds for a developing a new technique to fingerprint diagenetic fluids. This project investigates the use of the stable isotopes of sulfur (^{32}S and ^{34}S) as possible diagenetic tools to ascertain the nature of the diagenetic environment, i.e. open marine, closed marine, sulfate reduction, and thermo-chemical sulfate reduction.

2009 Planned Projects

SHALLOW-WATER CARBONATES AND RESERVOIRS

- Glovers Reef from Satellite to Subsurface: Unraveling Morphometrics, Facies Distribution and Stratigraphy
- Assessing the Stratigraphic Heterogeneity of a Windward Platform Margin, Exumas, Bahamas
- Linkages between Geomorphology and Sedimentology along a Reef-Rimmed Shelf: Crooked-Acklins Platform, Southern Bahamas
- The Search for Sub-Orbital Sea-Level Changes in the Eolianites of New Providence Island, Bahamas
- Controlling Factors on Acoustic Properties in Low-Porosity Dolomites
- Evaluation and Modeling of Stratigraphic Control on the Distribution of Hydrothermal Dolomite Reservoir away from Major Fault Planes
- 3D Visualization and Fluid Flow Detection in Fractured Carbonates: Cretaceous Orfento Fm., Madonna Della Mazza, Italy
- Lidar, Outcrop and GPR Analysis of Solution-Enhanced Faults and Fractures: Cassis Quarry, France (Year 2)

DEEP-WATER CARBONATES

- Patterns in the Spatial Deposition of Deep-Water Coral Mounds in the Straits of Florida
- Geochemistry of Deep-Sea Corals from the Straits of Florida
- Petrophysical Characterization of Danian Deep-Water Coral Mounds, Faxe, Denmark
- Platform Margin Channeled Slopes: New Bathymetric Data from Northwest Providence Channel, Northern Bahamas
- Petrophysical Characterization of Cretaceous and Tertiary Carbonate Mass Gravity Flows
- The Origin of Carbon Isotopic Variations in Platform-Derived Sediments

MIXED CARBONATE-SILICICLASTIC SYSTEMS

- Plio-Pleistocene Reef Development in the Southern Dominican Republic: Reef Growth, Facies Geometry and a Changing of the Guard
- A Digital Atlas of the Cibao Basin Mixed System
- Facies, Geometries and Sequence Stratigraphy of the Mixed Carbonate-Siliciclastic System in the Neuquén Basin (Year 1)
- Petrophysical Properties of Mixed Carbonate-Siliciclastic Rocks

FUNDAMENTAL RESEARCH

- The Role of Early Cements in Maintaining Porosity and Permeability during Burial: Compaction Experiments
- The Influence of Interparticle versus Vuggy Porosity on Acoustic Velocity of Carbonates
- Vp/Vs Ratio in Carbonates
- Sulfur Isotopic Composition as a Tool in the Understanding of Diagenetic Carbonates

Costs

The contribution of each Industrial Associate towards the research is **$45,000**. The CSL raises additional research grants from national funding agencies such as the National Science Foundation and the Petroleum Research Fund for many of the proposed projects. For 2009, we have secured funding for most of our deep-water coral work, the 4D GPR projects, and the fundamental aspects of the geochemical studies.

Reporting

The results of the projects will be presented at the **Annual Review meeting in Miami October 5-6, 2009**. In conjunction with the meeting a fieldtrip to New Providence Island in the Bahamas is planned; the main theme of the trip will be the Pleistocene-Holocene stratigraphic succession and its heterogeneity. Tentatively the fieldtrip starts late on **October 6** with a flight to the Bahamas and **ends October 11, 2009**.

Shallow-Water Carbonates and Reservoirs

Glovers Reef from Satellite to Subsurface: Unraveling Morphometrics, Facies Distribution and Stratigraphy

Noelle J. Van Ee, Gregor P. Eberli, Harold R. Hudson[1], Eugene C. Rankey[2], Anton Eisenhauer[3] and Eberhard Gischler[4]

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Project Purpose

1) To retrieve cores in a N-S transect though the reef rim and patch reefs on Glovers Reef for an assessment of the nature and age of the antecedent topography that was observed on seismic data. The rotary core transect is also used to reconstruct a high-resolution sea-level history for reef development on Glovers with a focus on finding evidence for suborbital cycles in the Pleistocene and dating the Holocene reef initiation.

2) To construct facies and bathymetric maps using satellite images. The sedimentological and satellite aspect of this project aims to characterize the distribution and morphometrics of grainy facies belts across the platform. High-resolution IKONOS satellite imagery will allow wind-influenced asymmetric facies belts to be mapped on a decameter scale.

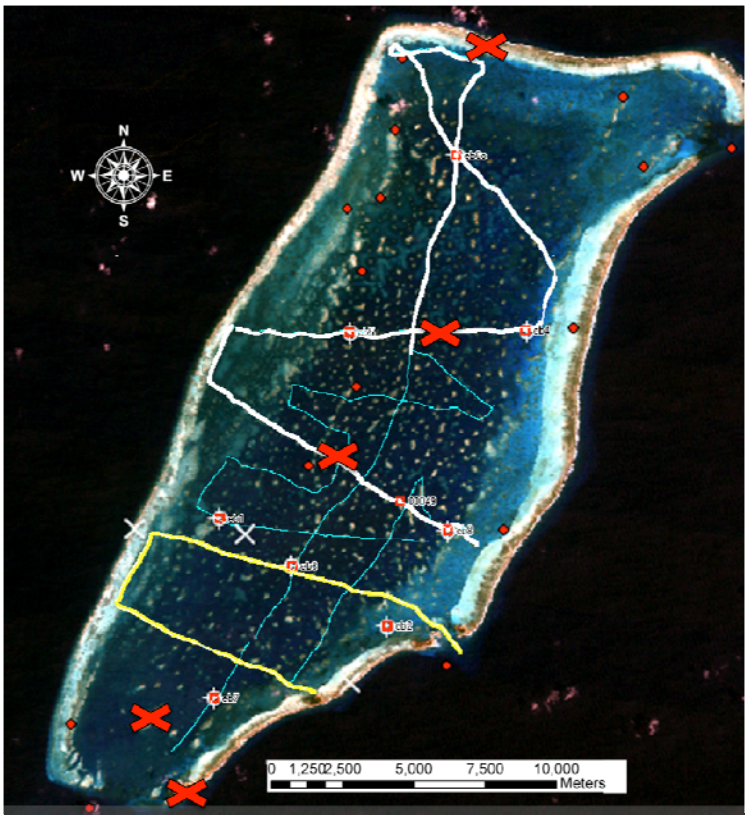

Figure 1: The locations of the potential drill sites are shown as red crosses. White, yellow and blue lines indicate the seismic grid collected in March 2008.

Scope of Work

We will collect Pleistocene rotary cores in a N-S transect across Glovers Reef, and examine these cores and three cores that were collected earlier by Eberhard Gischler along an E-W transect. The core material will be used to address several questions in regards to platform and sea level evolution, and it will provide material for U-Th dating. The goal is creating a high-resolution reconstruction of sea-level history and reef response on the platform. In a parallel effort, the analysis of satellite images will produce facies and bathymetric maps. These maps that are ground-truthed with sedimentological analyses will increase our understanding of modern geomorphic trends and aid core-constrained prediction into the subsurface.

Project Description

In March 2008, we collected shallow water seismic data imaging numerous lagoonal patch reefs and antecedent Pleistocene topography beneath the majority of them. We now plan to drill 3-5 cores in a N-S transect in order to determine the facies, diagenesis and ages of this topography; is it karst or reef? Two of these cores will be located on the marginal reef, the others on patch reefs (Figure 1). The N-S transect will allow us to determine if the Pleistocene is deeper toward the south than the north, i.e., if a tilting occurred in the Pleistocene. We also want to determine the age of the Pleistocene surface we are imaging, whether it is MIS 5e, 9 or 11? We aim to drill as far as possible into the Pleistocene with the hope of retrieving dateable material from several sea-level high-stands within the Pleistocene.

U-Th dates of the few Pleistocene corals sampled from previous Glovers Reef rotary cores have returned dates from 120-140 ka BP (MIS 5e) to 280 ka BP, a date which (surprisingly) suggests deposition during MIS 8 when sea level was 50 m lower than present (Gischler et al. 2000). In the southern Belize lagoon, stacked reefs were imaged seismically by Esker et al. (1998) and interpreted as the result of multiple sea-level high-stands within the Pleistocene, but no cores were taken. Therefore multiple sea-level high-stands may also be recorded on Glovers Reef. Our own seismic data has insufficient penetration to image multiple stacks of patch reefs on Glovers Reef. The proposed drilling deep into the Pleistocene and subsequent U-Th dating of the core material is expected to document the stages of sea-level highs and thus provide much needed information about the evolution of the entire reefal platform system.

Satellite images of Glovers are being integrated with depth information from reef transects and the seismic survey to create a three-dimensional visualization of the reef morphology and context for the sediment samples that have been collected (Figure 2). High-resolution IKONOS images are enabling asymmetric facies belts in response to wind direction to be mapped at a decameter scale for the first time on Glovers (Figure 3). The bathymetric and facies maps generated from this process will greatly increase current knowledge of controls on facies distributions and, therefore, aid prediction into the subsurface.

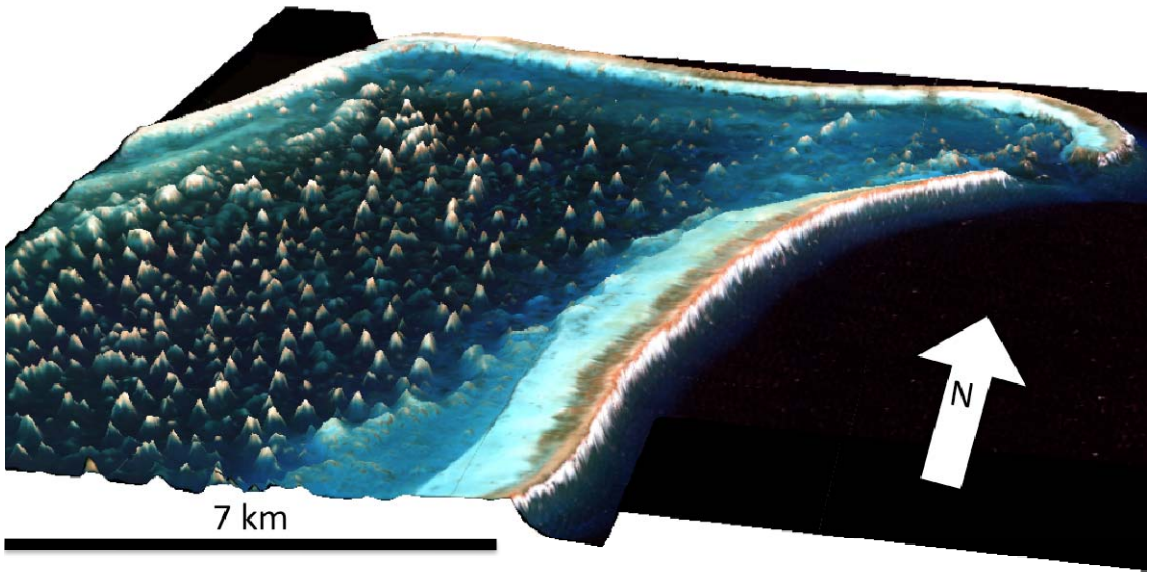

Figure 2: An IKONOS image and ENVI software were used to construct this three-dimensional bathymetric map of the northeast corner of Glovers Reef, displaying the continuous marginal reef and the broad, flat sand apron, the North-East channel that is the main opening for water exchange in northern Glovers, the variable topography of the numerous patch reefs within the lagoon.

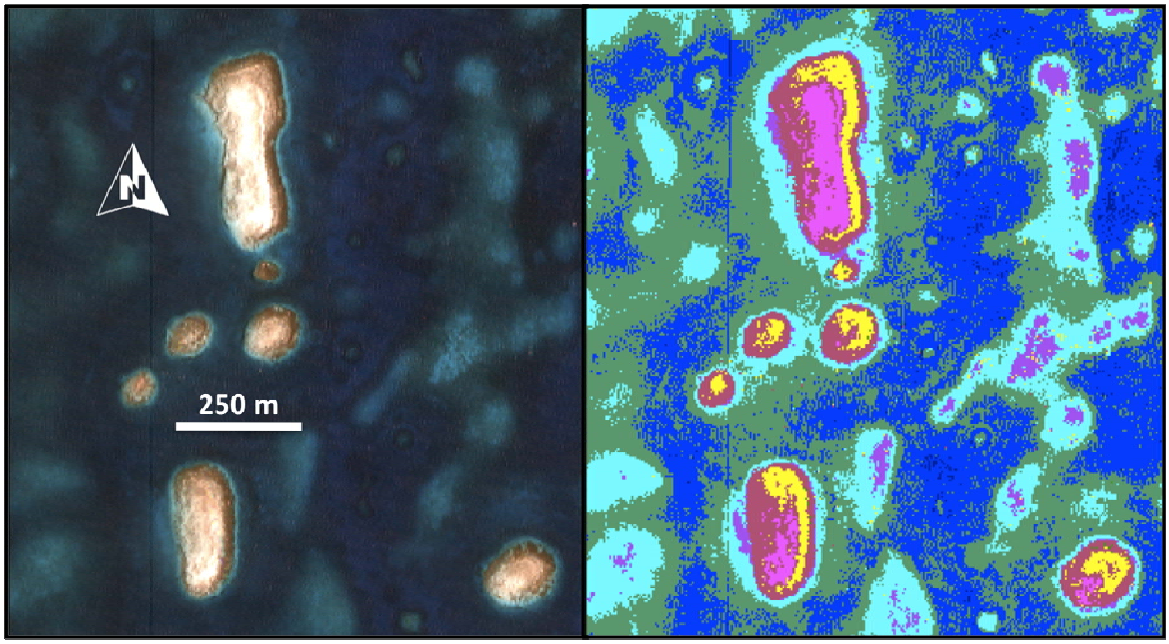

Figure 3: Left: High-resolution IKONOS images of path reefs. Right: Spectral analysis of the IKONOS image displays the decameter-scale asymmetry of the facies belts in the lagoon interior.

Key Deliverables

1. This project will provide an integrated assessment of morphometrics, facies distribution and quaternary stratigraphy and their linkages on Glovers Reef.
2. Core descriptions and sediment data will be placed in a satellite-based three-dimensional facies and depth context that will greatly aid the identification of morphologic, stratigraphic, and distribution trends.
3. Core descriptions will provide the facies and diagenetic information of the Pleistocene and Holocene cycles.
4. U-Th dates from corals will provide evidence for possible suborbital sea level stands within the Pleistocene and better constrain our interpretation of platform development in the Quaternary.

References

Esker, D., Eberli, G.P. and McNeill, D.F., 1998. Structural and sedimentological controls on the reoccupation of Quaternary incised valleys, Belize Southern Lagoon. AAPG Bulletin, 82, p. 2075-2109.

Gischler, E., Lomando, A.J., and Hudson, J.H., 2000. Last interglacial reef growth beneath Belize barrier and isolated platform reefs. Geology, 28, p. 387-390.

Assessing the Stratigraphic Heterogeneity of a Windward Platform Margin, Exumas, Bahamas

Kelly Jackson, Maaike Petrie, Gregor P. Eberli and Donald McNeill

Rationale

Sedimentary cycles produced by a high-frequency sea level change often form flow units in carbonate reservoirs. Platform interior cycles often maintain the same thickness over several kilometers and their vertical trends in thickness variations are used to delineate larger scale reservoir units. In a marginal setting with an inclined depositional topography the cycles vary greatly in shape depending on whether or not the rising sea-level floods over the precursor topography. Onlapping wedge-shaped deposits characterize those highstands that did not overtop the margin topography; those that flood the platform produce a thicker wedge but both primarily stacked laterally and prograde seaward (McNeill and Hearty, 2008). Because the elevation of each sea-level rise varies a complicated architecture of onlapping and overstepping wedges is produced. This project aims to comprehensively assess windward margin stratigraphy and heterogeneity by mapping the modern heterogeneity and coring the parasequence-scale stratigraphy along the windward margin in the Exumas. The goal is to provide a baseline for estimating heterogeneity in reservoirs in a windward margin setting.

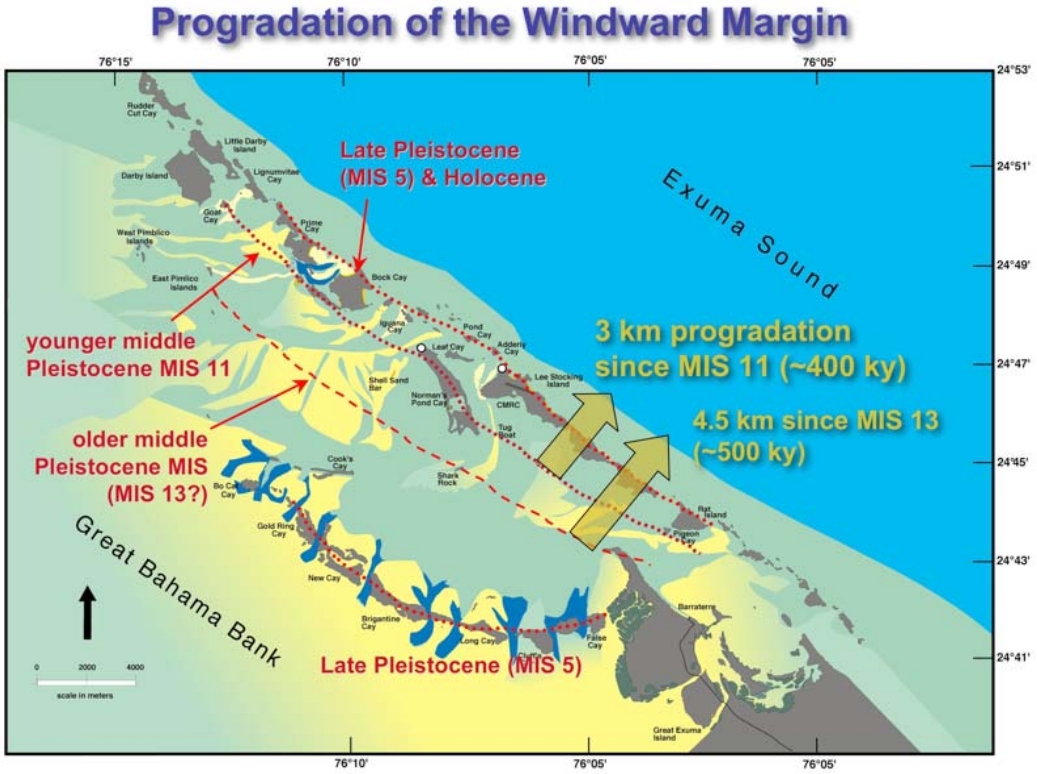

Figure 1: Surface map of the Pleistocene islands and modern grainstone shoals around Lee Stocking Island. Core borings and age dating of the Pleistocene strata reveal the heterogeneity of facies and stratigraphic succession as well bank margin progradation on this windward margin in the southern Exumas (from McNeill and Hearty, 2008).

Background

The results of two recently completed projects of the Pleistocene/Holocene strata along the windward margin of the Exumas reveal a complicated succession and juxtaposition of facies and ages (McNeill and Hearty, 2008). Likewise, surface mapping at Shroud Cay displays a lateral coexistence of Pleistocene eolianites, cemented Holocene storm beach ridges and modern grainy tidal flats (Petrie et al., 2008). Together these studies document the lateral and vertical heterogeneity of the grain-dominated windward margin that is produced by the sedimentary response to high-frequency sea level changes. In addition, the observed progradation questions the general assumption that windward margins stack vertically. Furthermore, the planned core borings provide the unique opportunity to decipher the amplitudes of the Pleistocene sea level changes and compare them to the amplitudes derived from the stable isotopes of open ocean foraminifera.

Scope of Work

The study area is situated in the Exumas, Bahamas, between Lee Stocking Island and Shroud Cay, connecting the two areas that were studied in previous years. The assessment of the heterogeneity and the underlying dynamics of the sedimentary strata will be accomplished by performing the following four tasks:

1. Produce a detailed geologic map of the margin by combining satellite imagery and surface mapping of the Pleistocene and Holocene strata.
2. Coring transects to establish the vertical successions at key locations.
3. Age dating of Pleistocene and Holocene using U-Th dating of corals.
4. Relating sedimentary successions to sea level fluctuations.

Expected Results

This project aims to decipher and document the stratigraphic heterogeneity of the Exumas windward platform margin and relate it to Pleistocene sea level fluctuations. The results from this project will provide an analog by which ancient windward platform margin heterogeneity can be compared.

References

McNeill, D.F. and Hearty, P.J., 2008., Progradation and Aggradation of a Windward Platform Margin, Exuma Islands, Bahamas. CSL Annual Meeting, abstract volume p. 49-52.

Petrie, M., Eberli, G.P. and McNeill, D.F., 2008, Sedimentology of Shroud Cay Sub-Environments: Tidal Flat, Tidal Delta, and Cemented Deposits. CSL Annual Meeting, abstract volume p. 59-63

Linkages between Geomorphology and Sedimentology along a Reef-Rimmed Shelf: Crooked-Acklins Platform, Southern Bahamas

Fikril Hakiki and Eugene C. Rankey[1]

[1]*Kansas University*

Project Purpose

Reef-rimmed shelves of many carbonate platforms are characterized by morphological rims, such as barrier reefs, and can have variable sedimentology and morphology. Characterizing the spatial heterogeneity of their sediments in modern carbonate systems is one means to better understand the potential complexity of ancient analogs. However, the details of spatial geomorphic and sedimentologic patterns on reef-rimmed shelves have not been widely documented or quantified. By integrating sedimentologic and remote sensing data, this study aims to describe and evaluate the depositional patterns and processes that influence sedimentary and geomorphic patterns on a reef-rimmed shelf on part of Crooked-Acklins Platform in the southern Bahamas.

Scope of Work

This project will evaluate sedimentologic data, detailed bottom observation and bathymetric data collected in the field. The preliminary results of laboratory analyses of these data, including petrographic analysis, show granulometric pattern of the sediments, as influenced by the geometry and morphology of the reef margin. In the near future, hydrodynamic measurements will be collected to explore processes (waves and tides) that influence facies heterogeneity in this area. The results will be integrated with the sedimentologic data and remote sensing analyses to better describe and understand the morphology and geometry of the shelf and the reef margin.

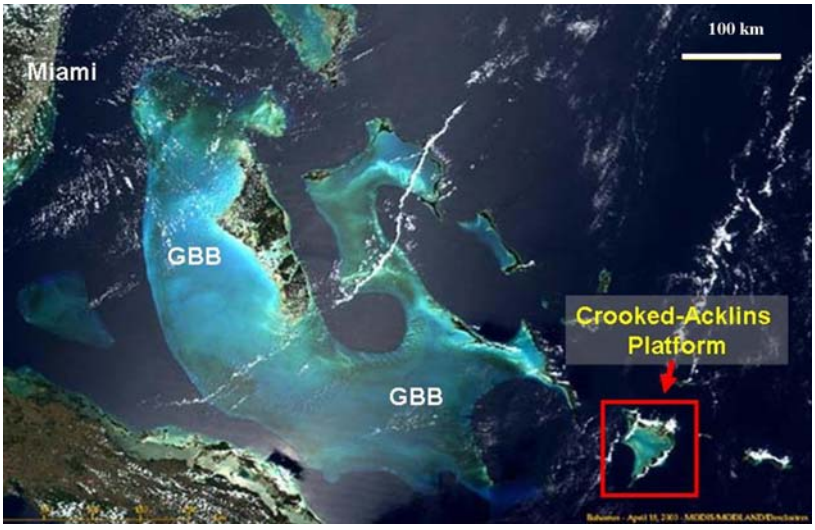

Figure 1: General location map of Crooked-Acklins Platform study area.

Key Deliverables

This study will provide the result of field observation and sedimentologic analyses of sediments on a reef-rimmed shelf on part of Crooked-Acklins Platform in the southern Bahamas. Further analyses on hydrodynamic and remote sensing data will provide information on the depositional processes and facies heterogeneity of sediments, including geomorphology of reef margin, in the study area. This information can provide an example of the potential heterogeneity of reservoir analogs.

Project Description

Reef-rimmed shelves are common geomorphic part of carbonate system in modern and ancient reef complexes. In ancient deposits, they can form important hydrocarbon reservoirs, in part because they commonly have thick porous sediment and permeable sediments (e.g., James and Ginsburg 1979; Pomar and Ward, 1999). To better understand these important, several Holocene reef complexes have been studied, mainly by drilling (e.g. Yamano et al., 2001; Tudhope and Scoffin, 1984). These studies focused on the mineralogy and the internal structure of back-reef facies but did not take into account spatial context, which is very important for understanding the scale, trends, and interrelationships of facies in the geologic framework. Additionally, to fully understand the facies heterogeneity in reef-rimmed shelves, the physical process influencing the sedimentation, spatial geomorphic and sedimentologic pattern from various back-reef systems must be better understood.

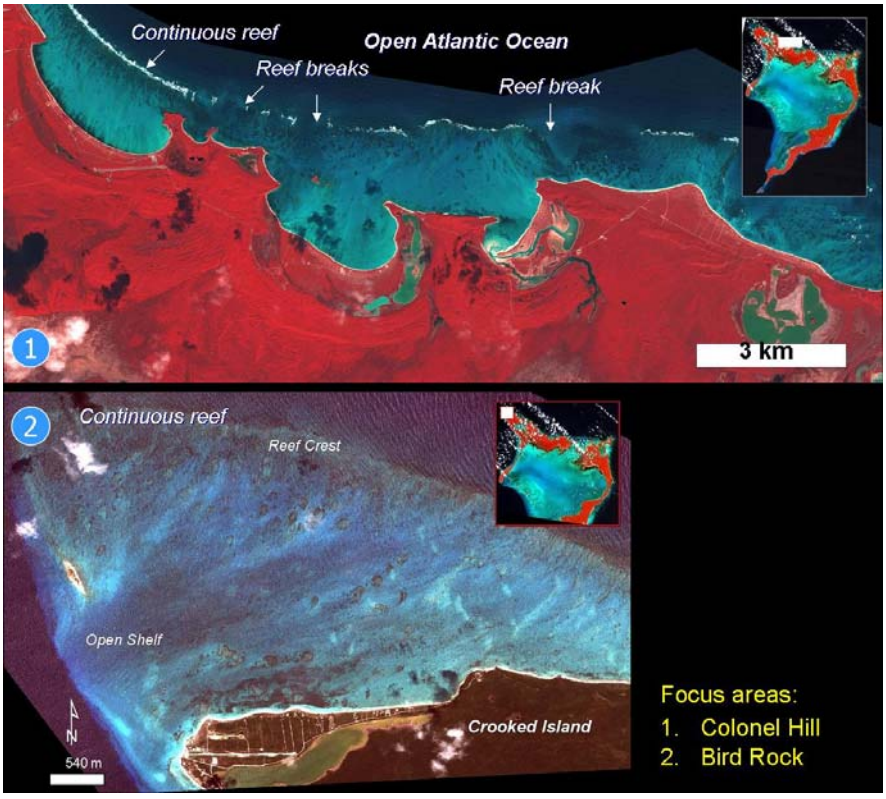

Figure 2: Two focus areas in the Crooked-Acklins Platform: (1) Colonel Hill area and (2) Bird Rock area

To capture the range of geomorphic variability, two focus areas will be closely examined (Figure 2). The first area is located offshore of the middle part of the Crooked Island, and has a reef margin facing to the north-northeast. The second area is located in the northwesternmost point of the platform, includes a well-developed reef margin facing northeast to north, but is open (unrimmed) to the west.

Roughly 200 superficial sediment samples, and bathymetric data, have been acquired in the study area. Sedimentologic and petrographic analyses characterize granulometric pattern and distribution of different types of sediments. The results can be compared with high-resolution (2.4 m resolution) QuickBird to provide information about general sedimentologic patterns and their relationship to the morphology of the barrier reefs and water depth. Field and laboratory analyses suggest that the sediment properties vary along and across the shelf margin, and are related to the continuity of the reef margin (Figure 3).

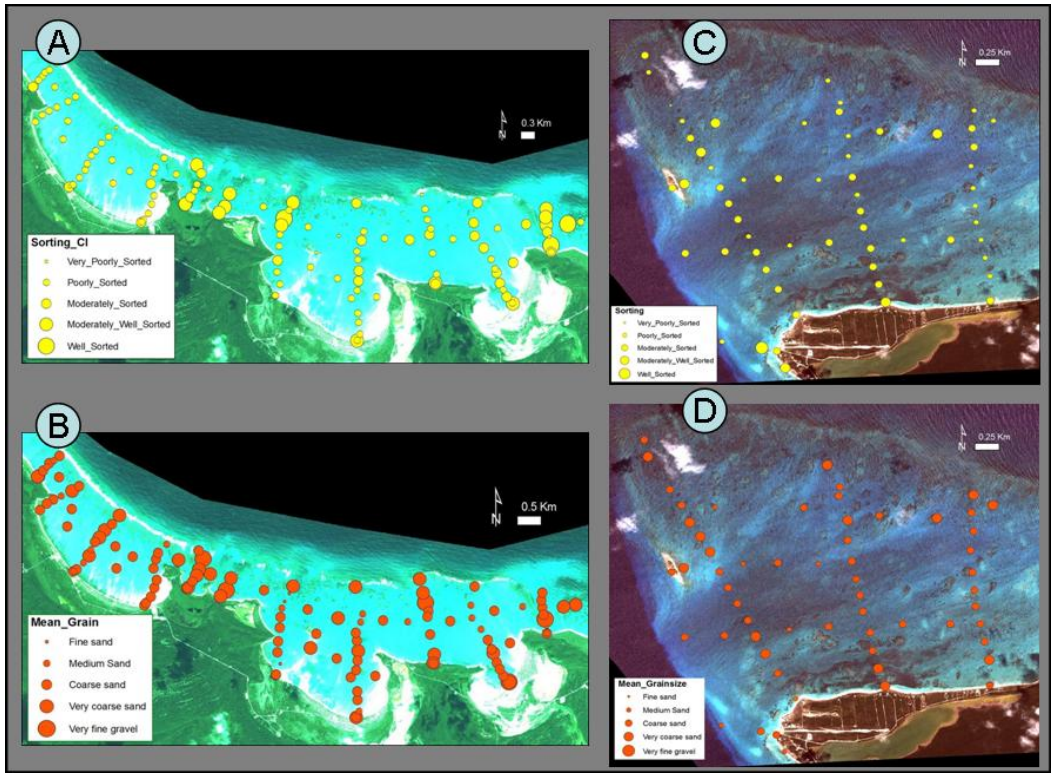

Figure 1: Granulometric characteristic of sediment in the study area: (A) Sediment sorting in Colonel Hill area, (B) Grain size distribution of sediments in Colonel Hill area, (C) Sediment sorting in Bird Rock area and (D) Grain size distribution of sediment in Bird Rock area.

This year, the study will be continued by characterizing wave and current patterns in one part of the shelf, testing concepts concerning the hydrodynamic process that might control the sedimentary patterns. Furthermore, these data will be integrated with remote sensing analysis to understand the relations among grain properties of sediments to geographic factors or spatial context.

Expected Results

By integrating sedimentologic, petrographic, and remote sensing analyses, this study will provide insights for the controls on the distribution and nature of reef margin and back-reef shelf sedimentology. We also expect to find that hydrodynamic processes, influenced by different reef margin morphology, exert a strong control on bottom morphology and granulometric properties of sediments. Furthermore, from these observations and interpretations, we expect to develop testable models that could be used for prediction in subsurface analogs.

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The Search for Sub-Orbital Sea-Level Changes in the Eolianites of New Providence Island, Bahamas

Samuel Reid, Gregor P. Eberli, Donald F. McNeill and Klaas Verwer

Purpose

New Providence Island is contains several outcrops with Pleistocene beach successions and eolianites, which combined with core material, will provide much needed information of the facies relationship, the stratigraphic succession and the reservoir potential of these facies. In addition, these outcrops might record a short-lived sea level fluctuation of approximately 10 m during the last interglacial (isotope stage 5e) that has been postulated based on coral data (Thompson and Goldstein, 2005). If such sub-orbital sea-level changes indeed leave a stratigraphic record, they would question assumptions in cyclostatigraphy. Our working hypothesis is that a pronounced unconformity within the eolianites on New Providence Island is caused by such a short-lived sea level change.

Methods

To document the stratigraphic architecture of the beach and eolianite facies outcrops will be examined throughout New Providence Island. Localities will be mapped on high resolution satellite imagery and will be plotted using GIS in order to refine the mapping work that has been done on New Providence Island in the past (Fig. 1). Within each sequence of eolianite deposition, shells of the land snail *Cerion sp.* will be collected for accurate radiometric dating.

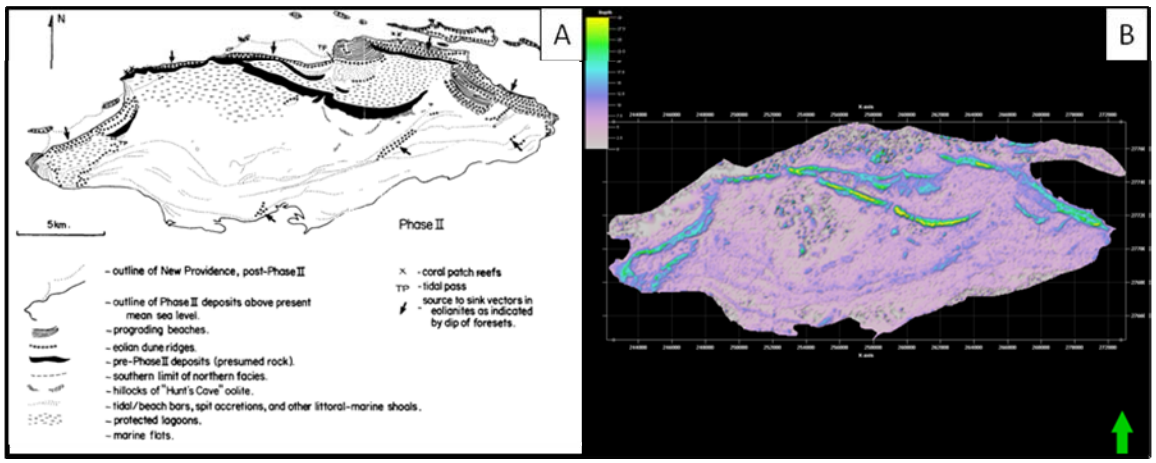

Figure 1: These maps show the study area of New Providence Island. (A) Is a drawing from Garett and Gould (1984) showing the lateral relationships of the deposits. (B) Is a false color image showing the altimetry of New Providence Island.

Background and Project Description

Carbonate eolianites are common deposits leeward of beach ridges and tend to mimic the shapes of the beaches themselves. These dunes can vary in lateral continuity and in height, but generally form just above sea level. Consequently, a drop in relative sea level

will create a hiatus in the record, which can be observed as an unconformity in outcrop. New Providence Island has several eolian dunes (they form the highest points) and many other ridges (Fig. 1). The southern ridges are beach ridges by Garrett and Gould (1984). Within the eolianites Garrett and Gould (1984) identified three major phases of dune formation in 13 outcrops on New Providence Island and subdivided individual phases into smaller sections based on internal discontinuity surfaces. Dating relied on biostratigraphy of *Cerion sp.* and some sparse radiometric dating. Overall, they correlated Phases I and II to previous Pleistocene highstands. Aurell et al. (1995) examined the Pleistocene beach successions in cores recovered from Clifton Pier. They identified four sequences since the beginning of the Brunhes Normal Chron (~0.78 Ma) and correlated the third sequence to Phase Ia of Garrett and Gould (1984).

We plan to rigorously correlate coeval beach deposits with the adjacent eolianites to unravel the dynamics of the facies successions through several Pleistocene sea level cycles. A special focus will be given to the last interglacial to document the sedimentary record of a sub-orbital sea-level cycle. Starting point of the fieldwork will be the numerous outcrops studied by Garrett and Gould (1984) followed by new road cuts. The cores used by Aurell et al., (1995) are in stored in Miami and we will search for more core material. The chronology of the eolian deposition will be unraveled by radiometric dating of multiple samples of *Cerion sp.*. Coupled with better radiometric dating, detailed outcrop analyses and mapping will help to refine the geology of New Providence Island.

Key Deliverables and Expected Results

This study will add both resolution and digitization to original geological work done on New Providence Island (Garrett and Gould, 1984). Together, these data will provide a dimensions carbonate beach and eolian succession both vertically and laterally. In addition, better radiometric dating will allow for more precise correlation between beach successions and eolianites. In addition, to a better understanding of the geological history New Providence Island and the Bahamas platform, we expect to add new insight to response of the carbonate environment to sub-orbital sea level changes. With higher resolution mapping and better dates on each of the sequences, a strong correlation with the oxygen isotope sea level curve is expected, which will test our hypothesis that suborbital sea level cycles can produce a stratigraphic succession the shallow-water carbonates.

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Controlling Factors on Acoustic Properties in Low-Porosity Dolomites

Laura Galluccio[1], Klaas Verwer, Gregor P. Eberli and Alessandro Iannace[1]

[1]University of Naples, Italy

Project Purpose

In carbonate rocks, velocity-porosity and porosity-permeability relationships are strongly influenced by both complicated textures and pore types. In low porosity rocks (< 10%) velocity variations cannot be explained by variation in pore types due to the inherent absence of an actual pore structure. Our working hypothesis is that in low-porosity carbonates variations in acoustic velocity are mainly controlled by grain-to-grain or crystal-to-crystal coupling. To test this hypothesis we will use acoustic laboratory measurements, assess the pore structure with digital image analysis, and evaluate the crystal-size distribution using petrographic observations and innovative GIS feature-extraction methodologies on thin section images. The findings are of fundamental significance to understanding acoustic wave propagation in low-porosity rocks, and of importance in evaluating analogous rock types in the subsurface using geophysical methodologies.

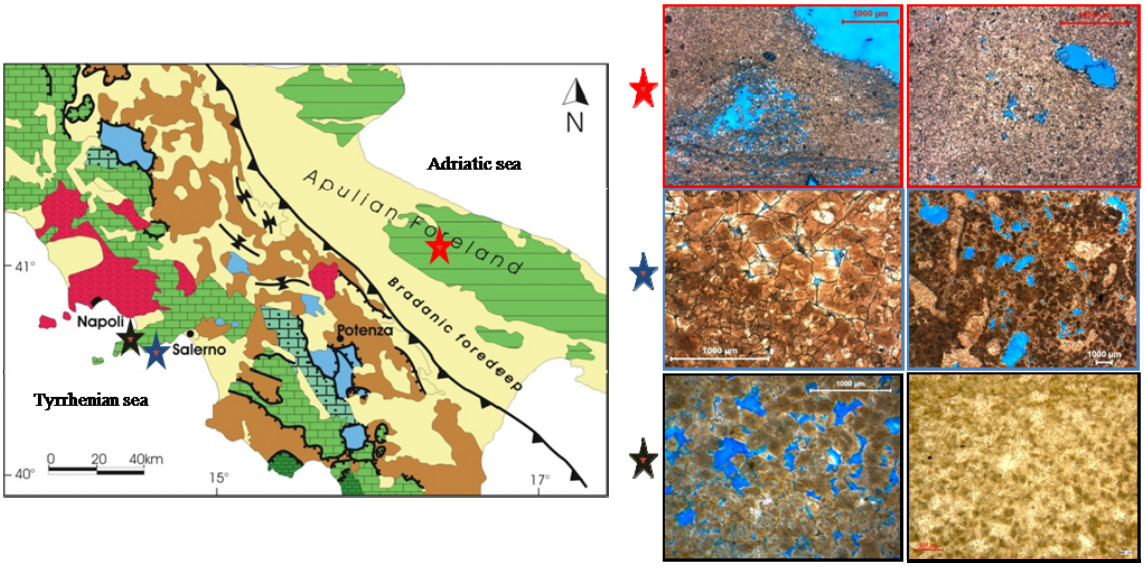

Figure 1: Left: Outcrop location in the Southern Apennines on geological map. Right: Photomicrographs of samples displaying characteristic textures of the dolomites from the different study sites: 1) red star: Cretaceous samples from Calcare di Bari; 2) blue star: Jurassic samples from the Sorrento Peninsula; 3) black star: Cretaceous samples from the Sorrento Peninsula.

Rational and Aim

Previous years CSL has investigated how different pore structures exhibit distinct velocity-porosity trends in carbonates. A major breakthrough in understanding velocity-

porosity variation in carbonates came through the quantitative assessment of the pore structure by digital image analysis from thin sections (Weger 2006). He identified two geometrical parameters most influential to acoustic velocity: perimeter over area (PoA) and dominant pore size (DomSize). These parameters capture the geometrical characteristics of pore edginess and pore size and satisfactorily explain variations in velocity in a range of high porosity rocks from 10 to 60%. In rocks with low porosity (< 10%) variations of the pore structures cannot be considered the main cause of variations in acoustic properties, mainly because of the limited amount of pores. This is especially true for low-porosity dolomites as their rock texture is composed of dolomite crystals of various size and hedral quality. Both size and shape of the crystals, however, control the crystal coupling. In Sun's Extended Biot Theory the frame flexibity factor γ describes the coupling of grains and crystals (Sun et al. 2001) and variations in γ should be reflected in variations of the acoustic velocity at these low porosities.

The aim of this project is to evaluate how intrinsic factors affect the acoustic properties in low-porosity dolomites. Digital image analysis (DIA) parameters will be correlated with sonic velocity measurements. The relationship between intrinsic parameters and the acoustic behavior will be incorporated and tested in Sun's Extended Biot Theory.

Project Description

The project will utilize three different sample-sets of low-porosity dolomites from the Sorrento Peninsula and Calcare di Bari (Southern Italy). The workflow will be the following:

1. Measure Vp, Vs values and porosity data at identical effective pressure steps.
2. Perform CSL digital image analysis on thin sections to assess the pore structure. Conduct an evaluation of the crystal-size distribution using petrographic observations and innovative feature-extraction from thin sections using GIS methodologies.
3. Evaluate scatter in acoustic measurements of acoustic properties as a function of intrinsic parameters, such as pore structure and crystal size distribution.
4. Establish controlling parameters on the acoustic properties of low-porosity dolomites
5. Test obtained relationships within Sun's Extended Biot Theory.

Key Deliverables

This project will provide an overview of the factors controlling acoustic properties in low-porosity dolomites.

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Evaluation and Modeling of Stratigraphic Control on the Distribution of Hydrothermal Dolomite Reservoir away from Major Fault Planes

G. Michael Grammer[1], William B. Harrison[1], Peter K. Swart and Gregor P. Eberli

[1]*Western Michigan University*

Project Hypothesis

Reservoir quality and distribution in fractured, hydrothermal dolomite reservoirs has historically been attributed to faulting and fracturing associated with regional wrench tectonics. Exploration and production strategies are typically focused on identifying fault trends and associated seismic sags. A problem, however, is trying to understand lateral variability in reservoir quality away from the major fault zones and the resulting presence of close step-out dry holes. Our hypothesis is that the lateral variability of reservoir quality hydrothermal dolomites away from the major fault zones is related to both the primary depositional facies and the sequence stratigraphic framework. We plan to test of this hypothesis in the giant Ordovician Albion-Scipio trend of southern Michigan because of the availability of extensive well, core and production data and because of access to recent 3-D seismic data from our industrial partner Polaris Energy (Figures 1 and 2). These results combined and 3-D reservoir modeling should lead to better predictability of laterally persistent reservoir zones in these systems and provide a means to enhance reservoir modeling at both the exploration and production scales.

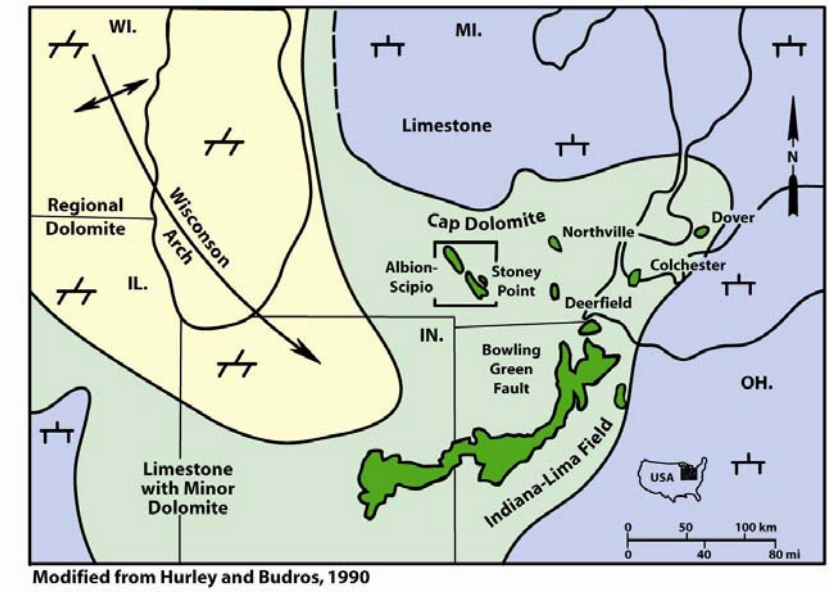

Figure 1: Map showing distribution of major known hydrothermal dolomite trends in and around the Michigan Basin. Total production from the Albion-Scipio trend (approximately 135 MMBO), Stoney Point field (approximately 12 MMBO) and the Indiana-Lima trend (>500 MMBO) are illustrated.

Background

Albion-Scipio field was discovered in 1957, but as with many mature carbonate plays in the U.S., the field has not been extensively studied using a state of the art reservoir characterization approach – i.e. one that incorporates depositional environment interpretation, diagenesis and reservoir potential into a robust sequence stratigraphic framework that would allow for enhanced predictability of the distribution of reservoir facies at exploration and production scales. This project will utilize subsurface data available for Albion Scipio, including cores and core analyses, thin sections, sample, fluid and gas geochemical data, wireline logs, drill cuttings, drillers reports, and production data.

Goals

1) to evaluate the degree of control that primary depositional facies has on current reservoir variability, and to determine how reservoir quality units that developed laterally away from the major fault zones are controlled by these primary facies and their position within a sequence stratigraphic framework;

2) to correlate laboratory measured sonic velocity data from various reservoir and non-reservoir facies to sonic logs and 3-D seismic signatures; and

3) to produce 3-D stratigraphic and reservoir models using Schlumberger's 3-D Petrel modeling software that will be tested with recently drilled wells.

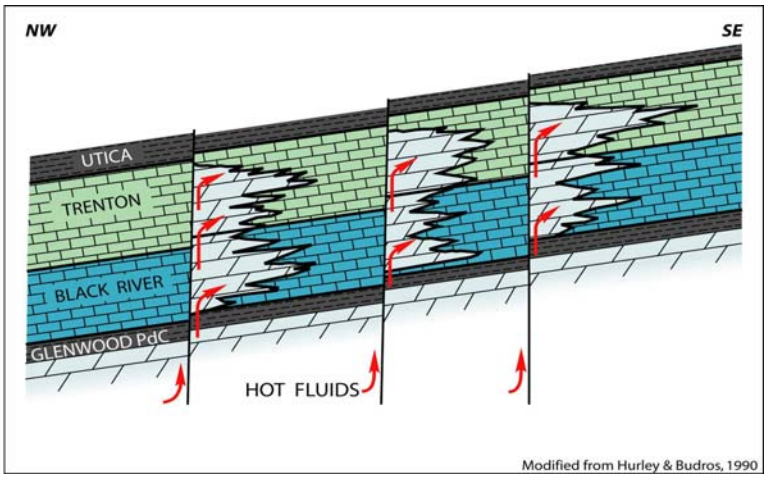

Figure 2: Albion-Scipio model for hydrothermal dolomitization. Dolomitizing fluids are concentrated along fault-controlled conduits and typically dolomitize rocks close to the fault plane. The lateral extent of reservoir dolomite is illustrated schematically to vary vertically

Expected Results

Results of this integrated project should lead to reduced exploration risk and increased production from similar mature plays by providing viable models for predicting and interpreting the stratigraphic control of hydrothermal dolomite reservoirs away from main fault trends. The correlation of sonic velocity to pore architecture and reservoir permeability will provide an immediate means to high-grade target zones from sonic log data and may provide enhanced exploration capability when combined with 3-D seismic interpretation.

3D Visualization and Fluid Flow Detection in Fractured Carbonates: Cretaceous Orfento Fm., Madonna della Mazza, Italy

Pierpaolo Marchesini, Rizky P. Sekti, Gregor P. Eberli, Mark Grasmueck, Brita Graham-Wall[1] and Paul Gillespie[1]

[1]StatoilHydro, Norway

Project Objectives

The overall goal of this project is to produce a comprehensive fracture and deformation band analysis including preferential flow paths of the Cretaceous reservoir analog in the Madonna della Mazza quarry in the Maiella Mountains, Italy. This analysis will include the following tasks:

1. High-resolution 3D visualization of the strata, fractures and deformation bands using 3D Ground Penetrating Radar (GPR).
2. Integration of structural information into stratigraphic and petrophysical characterization
3. 3D fracture analysis of GPR cube using Antracking™
4. 4D GPR experiment to track and quantify fluid flow within the strata, fractures and deformation bands
5. Simulation model of the GPR volume, using a HAVANNA/ECLIPSE simulation and comparing it with the fluid flow experiment

Background and New Opportunities

This collaborative project has its foundation in the 2008 acquisition of high-resolution 3D GPR data in the Madonna della Mazza quarry. The quarry in the northeastern limb of the four-way closure Maiella anticline is a popular site for detailed structural- and fracture analysis of the Upper Cretaceous strata (Orfento Formation) and serves as an analog for mildly deformed Cretaceous hydrocarbon reservoirs.

Figure 1: (A) Part of line drawing of deformation bands on the quarry floor by Tondi et al. 2006. (B) Aerial photograph of the same area; 20 m x 20 m wide. (C) Horizontal slice at 40 cm depth through one of the 3D GPR volumes displaying the deformation bands in great detail. The yellow arrow represents the direction of GPR data acquisition.

Tondi et al. (2006) conducted a detailed analysis of the quarry's structural features, documenting at least six sets of deformation bands that are produced either by compaction and shear strain localization, or through stylolites formed by pressure solution and subsequent shearing of these stylolites. In 2008 we tested if these deformation bands can be imaged with the GPR. Indeed, the 3D GPR surveys accurately image fractures and deformation bands in the subsurface (Figure 1). This visualization of the deformation bands gives the opportunity to investigate several fundamental aspects structural deformation at the 1-10 scale in carbonates. For the first time, the curvature and 3D geometry of the deformation bands can be analyzed and cross-cutting relationships of the different generations can be seen in space. In addition, the GPR cubes with their stratigraphic and structural information can be used as input cubes for fluid flow modeling. Finally, a fluid infiltration experiment and subsequent repeat GPR surveys can track and quantify the fluid flow in the strata, thus providing important information on the permeability characteristics of and across the deformation bands.

Scope of Work for the Individual Tasks

3D visualization of the strata, fractures and deformation bands: Six different GPR volumes using three different antenna frequencies (100 MHz, 200 MHz and 250 MHz) were acquired on the main level of the quarry (26 x 64 m). These volumes will be further processed and attributes (i.e. semblance and coherence attribute) will be applied for enhancing the visualization of fractures and deformation bands.

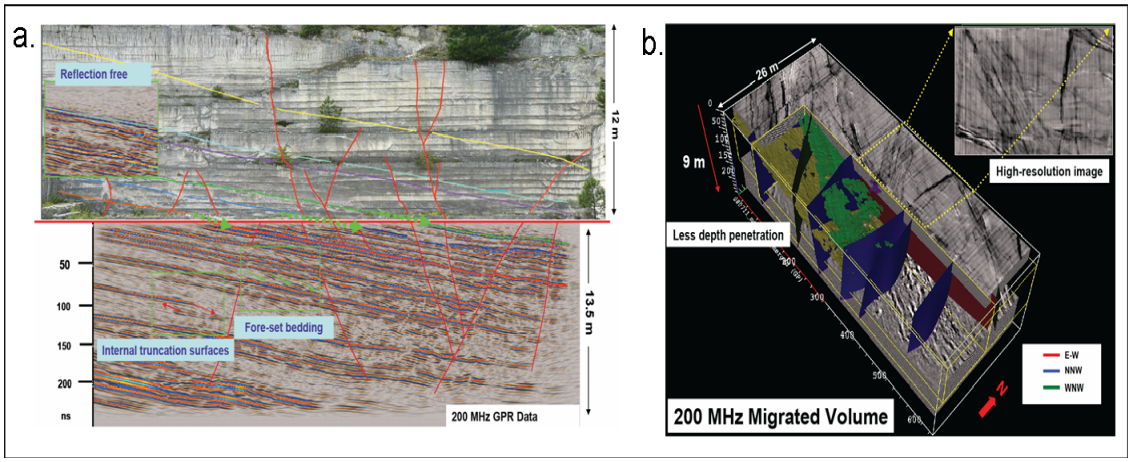

Figure 2: a). Quarry wall with fractures and bedding surface traced into the subsurface in the 100Mhz GPR volume. b). 200 MHz migrated volume with stratigraphic and fracture interpretations.

Integration of structural, stratigraphic and petrophysical data: For a comprehensive characterization of the deformed strata the stratigraphic heterogeneities and their petrophysical properties will be integrated. Petrography analysis from thin section and SEM will provide information of the diagenesis of the strata. Digital image analysis will quantify the porosity structure of the matrix. The petrophysical analyses of the matrix and deformation bands will include porosity, permeability and sonic velocity.

3D fracture analysis of GPR cube using Antracking™: This task will be performed in collaboration with Brita Graham-Wall and Paul Gillespie. The 3D analysis of the deformation bands using Petrel will provide a statistical analysis and will be used for a comparison with the outcrop-based analysis.

4D GPR experiment to characterize fluid flow: For detecting and quantifying fluid flow at the 1-10 m scale we will perform time-lapse Ground Penetrating Radar (GPR) experiments for tracking of infiltrated water at different time scales. GPR is very sensitive to changes in subsurface water content, and can therefore be used to monitor wetting and drying events in the unsaturated zone. If a 3D GPR survey is repeated with identical geometry (Grasmueck and Viggiano, 2007) changes in the GPR signatures must be due to the movement of water within the subsurface. Automated extraction of time shifts between time-lapse 3D GPR surveys and application of the Topp petrophysical transfer function (Topp et al., 1980; Huisman et al., 2003) yields the in-situ water content changes between repeat surveys. The water content change volumes are co-rendered as a semi-transparent attribute together with the regular 3D GPR data. Thus the most active flow zones can be identified and inferences can be made which stratigraphic and structural elements act as baffles or preferential flow paths. In our previous 4D GPR experiments within the Miami Oolitic Limestone, mass balancing has shown that volumetric water content change estimates from the 4D GPR method are accurate within a few percent. By decreasing the time interval between repeat surveys to 3 hrs the momentary wetting and draining fronts of the evolving water bulb could be resolved.

Figure 3: Location of the proposed ponded infiltration experiment on the Tondi et al (2006) map (blue square). The larger stippled square is the footprint of the repeat 3D GPR surveys. To avoid GPR antenna surface coupling artefacts we will construct a temporary pond using white plastic sheets (see inset). After all water has infiltrated, the pond walls are removed and the first post-infiltration GPR survey can be recorded.

Flow simulation model of the GPR volume: This task will also be performed in collaboration with Brita Graham-Wall and Paul Gillespie. It is planned to use a HAVANNA/ECLIPSE simulation but other simulations might also been used. The model geometry will be based on the 3D structural interpretation of the GPR surveys. The initial flow model will be populated with flow properties based on rock sample and plug measurements. This model is also used to help design the 4D GPR experiment (time interval between repeat surveys and amount of water to infiltrate). Once the 4D GPR data are acquired, flow simulation and GPR derived water content change volumes can be compared for an update of the flow simulation model.

Key Deliverables

- A comprehensive data set consisting of high-resolution GPR volumes, displaying the geometry of deformation bands and strata in three dimensions.
- A stratigraphic and diagenetic analysis of the rudist grainstone facies in the quarry, including quantitative digital image analysis parameters of the pore structure.
- Petrophysical measurements of the matrix and the deformation bands.
- 4D GPR volumes that visualize the progress of wetting fronts, pinpoint the preferential pathways, and quantify the fluid mass balance over time.
- Flow simulation cubes for comparison with the 4D GPR cubes.

Expected Results

The results of this multifaceted collaborative research effort is expected to provide new and insightful information of the role of deformation bands on the fluid flow behavior in Cretaceous rudist reservoirs.

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LIDAR, Outcrop and GPR Analysis of Solution-Enhanced Faults and Fractures: Cassis Quarry France (Year 2)

Miquel Coll[1], Juliette Lamarche[2], Kenri Pomar, Mark Grasmueck, Gregor P. Eberli, , Francois Fournier[2] and Jean Borgomano[2]

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Project Purpose

In many carbonate reservoirs the fracture network is one of the most important factors controlling fluid and gas flow. However, accurate characterization of fracture patterns at the reservoir scale is not an easy task because it requires both the understanding of the processes that control fracture development and the knowledge of the 3D geometry and connectivity. Our state-of-the-art laser-guided acquisition of 3D GPR data has the resolution and precision to accurately image faults and larger fractures to depths of up to 30m. Combined with LIDAR scanning and other information from the exposed outcrop we can build a comprehensive and accurate three-dimensional reservoir analogue model. In this collaborative project, we combine outcrop-based fracture analysis with 2D and 3D GPR analysis of late Barremian shallow-water carbonates in a quarry near Cassis (Figure 1) to obtain the best possible description of the origin of fractures, their distribution, connectivity and size. The outcrop and the subsurface based analysis will be compared for an assessment of the advantages and strengths of each method.

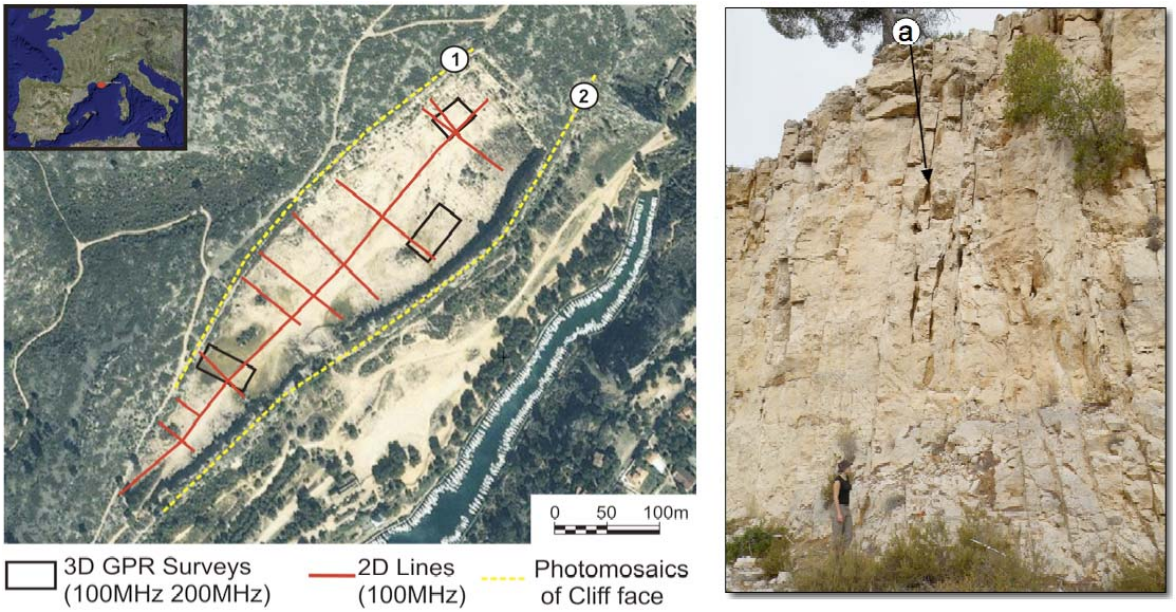

Figure 1: Left: Map of Cassis Quarry: The quarry is over 500 m long and approximately 100 m wide, allowing for the examination of production scale lateral variability of the fracture network. The location of the 2D and 3D GPR data acquired in 2008 is shown. LIDAR scans of the cliff faces adjacent to the Quarry floor will be acquired in 2009. Right: Near vertical fractures in the quarry wall. Marker a shows how some of the fractures are solution enhanced .

Scope of Work

During this multidisciplinary project a comprehensive suite of data will be produced, analyzed and compared. This is made possible by the collaboration of researchers from three Universities. The outcrop-based analysis of the fracture pattern is performed by Juliette Lamarche from Université de Provence. The strike, dip, size and spacing (in strike family) of fractures will be systematically measured, using the linear method, on the walls for statistical and geometrical analysis.

The 2D and 3D GPR data cubes (100 and 200 MHz), acquired in July 2008, will be further processed and analyzed to image the stratigraphic sequences and the fractures distribution in 3D with GPR with the best possible resolution.

Miquel Coll and his colleagues from Universitat de Barcelona will acquire a LIDAR data survey in the first quarter of 2009. The objectives are to scan the quarry floor and the cliff faces above and below the quarryfloor. For this data acquisition they use an Ilris3D scanner manufactured by Optech Co. A high-resolution geo-referenced model will be created using DGPS (Differential GPS). LIDAR data processing and interpretation will focus on mapping the beds and the fractures. All LIDAR, GPR and outcrop measurement data and will be imported to the GOCAD 3D modeling software for an integrated geological analysis.

Kenri Pomar from the University of Miami will concentrate his investigation on the process and distribution of the solution enhanced fractures. He will combine analysis of 3D GPR data with outcrop analysis for an assessment of the distribution of the solution enhancement.

Francois Fournier from Université de Provence will measure the petrophysical properties of the strata, including porosity, permeability and sonic velocity.

The comparison of the structural analysis from outcrop and LIDAR to the subsurface GPR data will be performed by the entire group for the construction of a comprehensive model of the fracture pattern and origin in the strata.

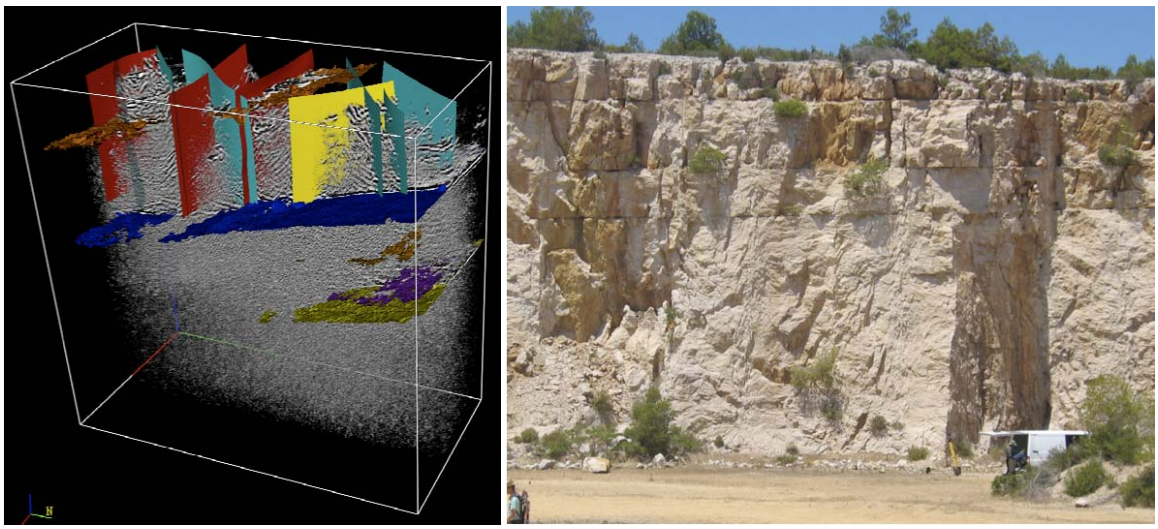

Figure 2: Left: GPR volume (values of minimum amplitude are removed) with stratigraphic and fracture interpretation. The blue horizon acts a mechanical unit boundary against which the large fractures terminate. Right: A major fault offsetting the quarry wall is one of the green faults interpreted in the GPR data. This fault like most fractures strike N080° and are sub-vertical.

Deep-Water Carbonates

Patterns in the Spatial deposition of Deep-Water Coral Mounds in the Straits of Florida

Thiago B.S. Correa, Gregor P. Eberli, Mark Grasmueck and John K. Reed[1]

[1] *Harbor Branch Oceanographic Institution, Fort Pierce*

Project Purpose

Spatial heterogeneity is a prominent characteristic of carbonate depositional systems. Examining spatial depositional patterns and quantifying the facies attributes of modern analogs is therefore a common approach to improving geologic models (Harris and Vlaswinkel 2008). Most studies of spatial patterns and facies attributes are performed in modern shallow-water analogues; an opportunity given by recent advances in mapping with high-resolution satellite imagery data (Rankey, 2002; Purkis et al., 2005). A few studies have attempted to characterize the distribution and morphometrics of deep-water carbonate systems (O'Reilly et al., 2003). However, the survey technologies in the deep ocean have been insufficient to resolve the geometry of depositional bodies. The high-resolution data set collected by an Autonomous Underwater Vehicle (AUV) in the deep-water coral mound environments of the Straits of Florida allow, for the first time, to characterize the morphometric parameters and facies distribution in a deep-water setting. This work will provide insights into the modern deep-water carbonate depositional systems, as well as improve our understanding of ancient systems.

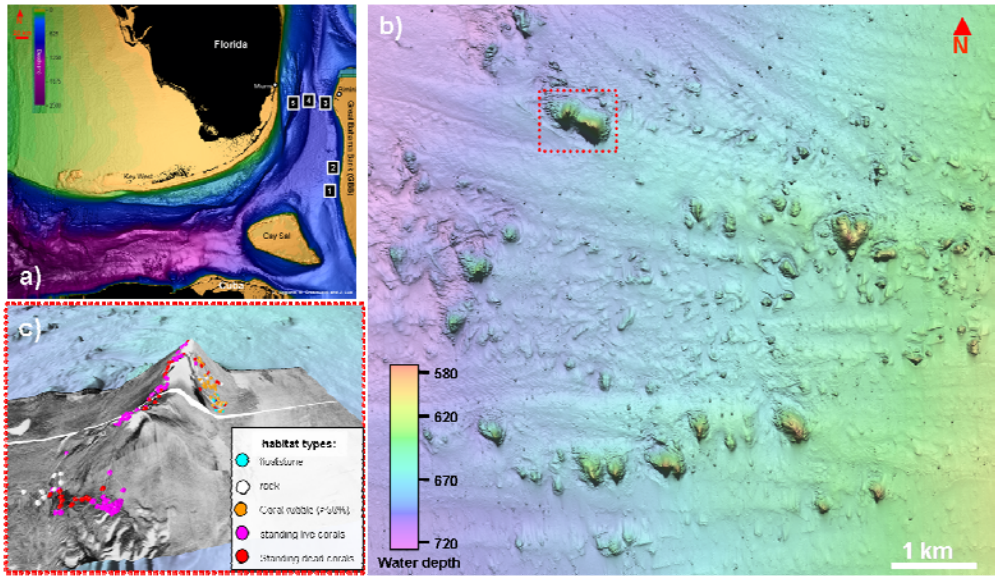

Figure 1: (a) Location of the AUV sites in the Straits of Florida. (b) Plan view of AUV multibeam map of site 1. More than 500 mounds were observed in a total area of 48km^2. Mound morphometric parameters (i.e. shape, height and orientation) are variable and will be quantitatively analyzed in this work. (c) Close-up view displaying overlaid side-scan sonar map and groundtruthing observations from the submersible video (each color corresponds to a different type of habitat). Habitat attributes will be extracted for the entire site.

Project Objectives

The objectives of this work are to: (1) calculate mound size, height, shape and spatial density of deep-water coral mounds in the northern Straits of Florida; (2) correlate mound

morphology and alignment with current strength and direction; (3) describe and quantify the facies attributes of these habitats; and (4) understand the spatial pattern of facies in deep-water environments- whether they are ordered and deterministic or driven by stochastic processes.

Project Description

This project uses an innovative, inter-disciplinary approach that combines high-resolution geophysical maps (multibeam and side-scan sonar) and submersible dives on five coral mound fields throughout the Straits of Florida (590 to 860m water depth). These maps cover a total area of 130km^2 and they are up to 50 cm resolution (i.e., 100-fold improvement in resolution from previous surveys). Multibeam maps will be used for the morphometric analyses. Each mound-like structure on the digital terrain maps will be analyzed in terms of its height, shape, orientation and footprint area. Side-scan sonar maps will be groundtruthed in order to determine the facies type at each site. The backscatter intensity values will be extracted from each ground-truthed facies. These values can then be extrapolated throughout side-scan sonar surveys to characterize the facies for entire site areas.

Key Deliverables

This project will produce quantitative analyses of morphometric parameters for deep-water coral mounds in the Straits. It will also generate a high-resolution, habitat characterization map for the deep-water carbonate system in the Straits. The lateral variability and the sedimentological attributes (i.e. grain size and composition) of each facies will be determined. A probabilistic analysis of the neighborhood pattern (i.e., facies-facies relationship) will also be performed in order to evaluate whether facies neighborhoods are random or deterministic. These analyses will determine statistically the controlling forces on mound distribution, geometry, formation and development.

Expected Results

The spatial statistic analyses of deep-water coral mounds and their associated substrate types, together with the development of habitat characterization maps will, for the first time, provide a quantitative assessment of a deep-water environment. The results will help to relate the major processes that govern mound formation and development to the morphometrics of the mound fields. Collectively, this information will aid in the interpretation of ancient deep-water carbonate environments as well as in the exploration for hydrocarbon in off-platform carbonates.

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Geochemistry of Deep-Sea Corals from the Straits of Florida

Angela D. Rosenberg, Peter K. Swart and Gregor P. Eberli

Project Purpose

The goal of this project is to utilize stable carbon and oxygen isotopes and trace and minor elements of drilled deep-sea coral skeletons to constrain environmental variations (temperature and salinity) across the Straits of Florida. In addition, the geochemical results will be compared to previously modeled data in order to ground-truth the East Florida Shelf – Princeton Ocean Model (EFS-POM). Successful use of geochemical analyses to reconstruct environmental changes will determine whether deep-sea corals can be used as a geochemical proxy in the Straits of Florida.

Scope of Work

Several specimens of *Lophelia spp*., *Madrepora spp*., and *Enallopsammia spp*. have been collected from sites across the Straits of Florida (locations 3, 4, and 5; Figure 1). Live coral skeletons are sampled using a computerized micromill and the drilled material analyzed using a stable isotope mass spectrometer and ICP-OES to determine concentrations of minor elements such as Sr, Mg, and Ba. The resulting data will be used to investigate the growth rates of the corals, as well as the bottom water conditions at the three specified locations in the Straits of Florida.

The geochemical results from coral skeletons across the Straits are also compared to data from the EFS-POM. Using the model, temperature profiles across the Straits of Florida with depth were created. Geochemical data from sampled coral skeletons is then compared to these profiles.

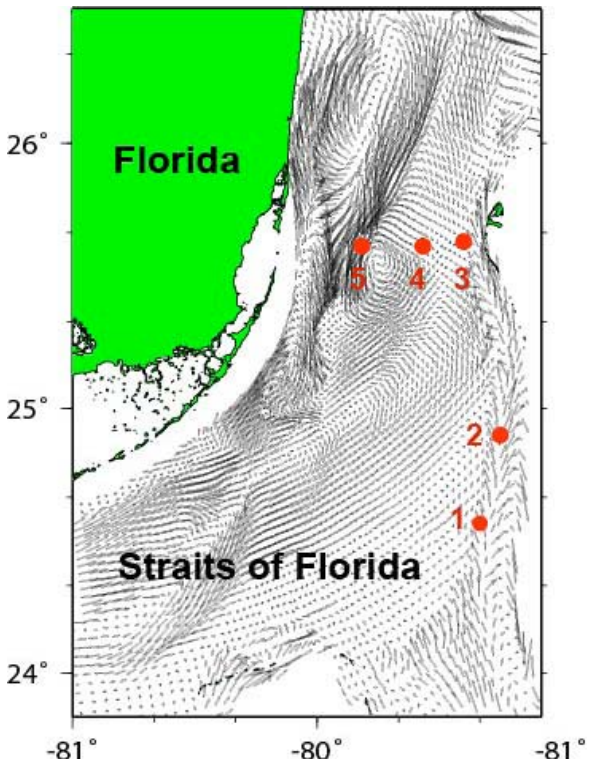

Figure 1: Near-bottom current pattern on Dec. 18, 2005 in the Straits of Florida, displaying a diverse current with cyclones and countercurrents. 1- 5 are locations of deep-sea corals sites.

Key Deliverables

The isotopic values and/or elemental concentrations of sampled deep-sea coral skeletons will indicate variations in bottom conditions at the three sites across the Straits of Florida through time.

Project Description

The stable oxygen isotopic composition of shallow water zooxanthellate corals can be used as an indicator of temperature and water isotopic composition (Fairbanks and Dodge, 1979; Weber and Woodhead, 1972). Similar annual variations occur in the $\delta^{13}C$ related to variations in the photosynthesis and the $\delta^{13}C$ of the ambient dissolved inorganic carbon (Swart et al., 1996). Cyclicity in the geochemistry of the skeleton through time may be used to determine the thickness of growth layers and, in turn, skeletal extension rates. Similar principles can be applied to cold-water azooxanthellate corals; however, the slow growth rates of the deep-sea corals make sampling difficult. Also, the range in the $\delta^{18}O$ is frequently reduced due to the low variability of water temperatures. This study proposes to use potential seasonal changes in the $\delta^{18}O$ and $\delta^{13}C$ to determine growth rate and bottom water temperatures in the Straits of Florida. Previous work has determined that there may be as much as a 4 -18^{o}C temperature change across the Straits. This raises the question of whether there are significant differences in seasonality across the Straits of Florida.

Expected Results

The stable isotope and minor element geochemistry of the coral skeletons will enable the determination of differences in environmental conditions across the Straits of Florida. The corals will act as multi-year *in situ* recorders of temperature.

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Petrophysical Characterization of Danian Deep-Water Coral Mounds, Faxe Denmark

Gregor P. Eberli, Ida Fabricius[1] and Klaas Verwer

[1] *Technical University of Denmark, Department of Environmental Engineering*

Project Purpose

Deep-water corals form impressive, up to 180 m high mounds on the sea floor from the deep seaways of the Bahamas across the North Atlantic into the North Sea. For example the 155 m high Challenger Mound, drilled in the Porcupine Basin during IODP Expedition 307, is constructed by an alternation of coral floatstone and wackestone units. In the Straits of Florida mounds can be as high as 120 m and coalesce to form km long ridges. Thus, their size and abundance make them potential but hitherto unexplored reservoirs. Little is, however, known about petrophysical properties of these mounds. In the early Cenozoic strata (Middle Danian) of Denmark large reefal mounds similar in size and shape of the modern ones occur in deep water carbonate settings. In the Faxe quarry, the reefal limestone is mined and offers the unique opportunity to sample the mounds and their associated facies. Earlier work by Danish scientists has described their composition and architecture. This project aims to characterize the mounds petrophysically.

The Fakse Quarry

The Faxe limestone quarry is dug into a pronounced topographic bank in which a complex of interbedded coral and bryozoan limestone banks of Middle Danian age are exposed. The most extraordinary feature at Faxe is the great coral bank complex.

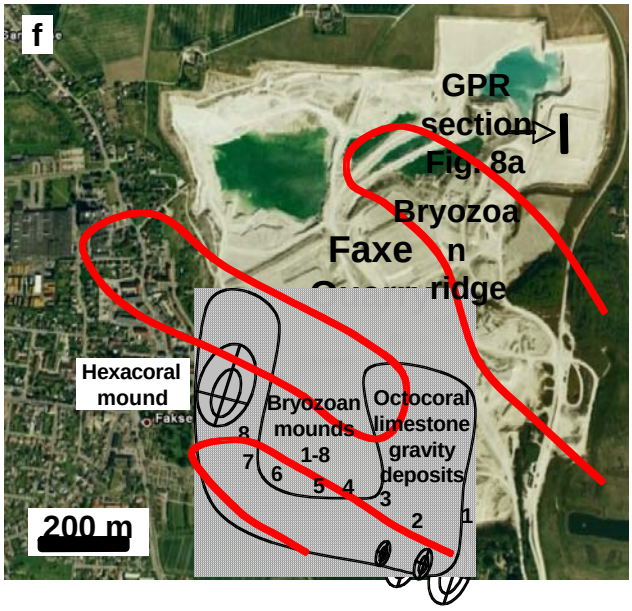

Figure 1: Aerial view and geological map of the Faxe quarry. The red lines outline the bryozoan ridges while hexacoral mounds and its associated facies dominate the crosshatched area.

The Faxe Mound, which is slightly elongate in the NW-SE direction and covers over 1 km^2, has an immensely rich fauna and has undergone some diagenetic alterations. The individual coral banks are up to about 20 m high and stacked mounds are estimated to be up to 100 m high. The coral banks are interbedded with bryozooan banks.

The coral mounds are predominantly built by 3 genera of ahermatypic scleratine corals: Dendrophyllia, Faksephyllia og Oculina. Other species of scleratines do, however, also occurr, as do octocorals and stromatoporide sponges. (For more details see http://geosites.dk/themes/danian_selandian/ds_fakse_kalkbrud/index.html).

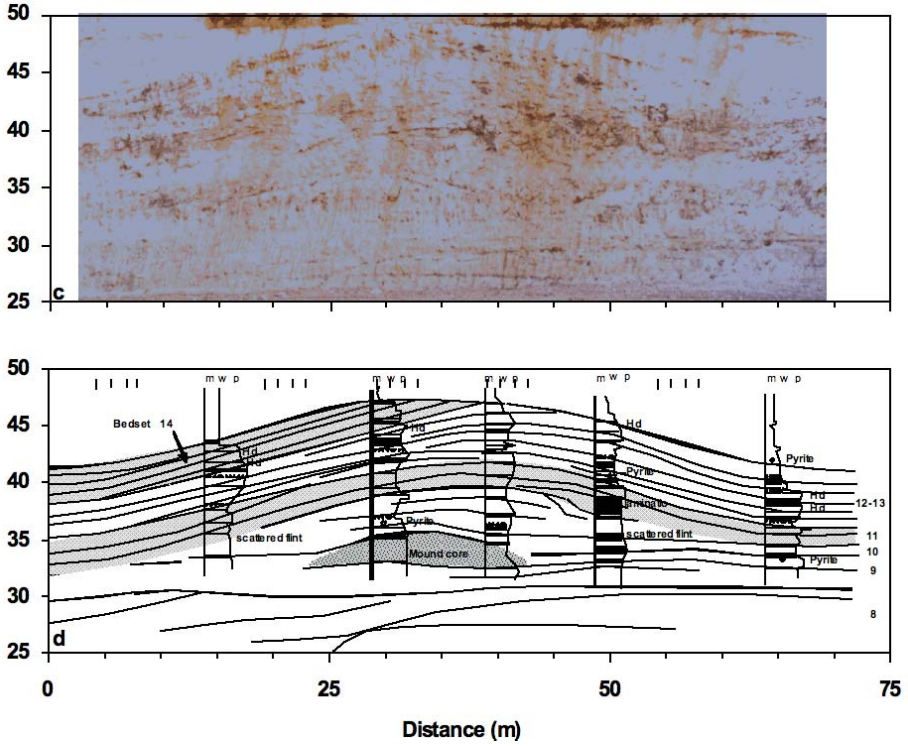

Figure 2: Photograph and line drawing of mound in the Faxe quarry, displaying the internal architecture of the deep-water coral reef.

Scope of Work

The geometry and texture of the mounds are assessed using photography and surface mapping. The main focus of the project is to measure porosity, permeability, sonic velocity and resistivity of the mound strata. In addition, the pore structure will be documented with quantitive digital image anlaysis parameters. The petrophysical measurements and the digital image analysis will be integrated into a sedimentologic and diagenetic characterization of the mounds.

Deliverables and Expected Results

This study will produce the first petrophysical characterization of deep-water coral mounds of Danian age. It is expected to provide a basis for evaluating the reservoir potential of deep-water build-ups of this and other ages.

Platform Margin Channeled Slopes: New Bathymetric Data from Northwest Providence Channel, Northern Bahamas

Donald F. McNeill and Gregor P. Eberli

Project Purpose

The lower slope of carbonate platforms are often dissected by channels that run perpendicular to the platform margin. These channels vary in size but quantitative data of both modern and ancient channels are scarce. This project aims to characterize the distribution and morphometrics of slope channels along the southern margin of Little Bahama Bank based on a large multi-beam survey. High-resolution bathymetric mapping of these slope channels will provide the scale of the channels. In addition, we will examine a possible relation of channel formation to downslope basin morphology.

Scope of Work

This project will examine multi-beam swath bathymetric data along the southern margin of the Little Bahama Bank platform. These new data provide an unparalleled image of the slope morphology, especially the occurrence of large channels within the intermediate slope (400-1000 m depth). The distribution and size aspects of the channels will be compiled and related to the overall basin configuration.

Key Deliverables

This project will provide some of the first measurements on the aspects and morphology of platform margin slope channels. Results will be presented at the Annual Review and images and data made available to the Industrial Associates.

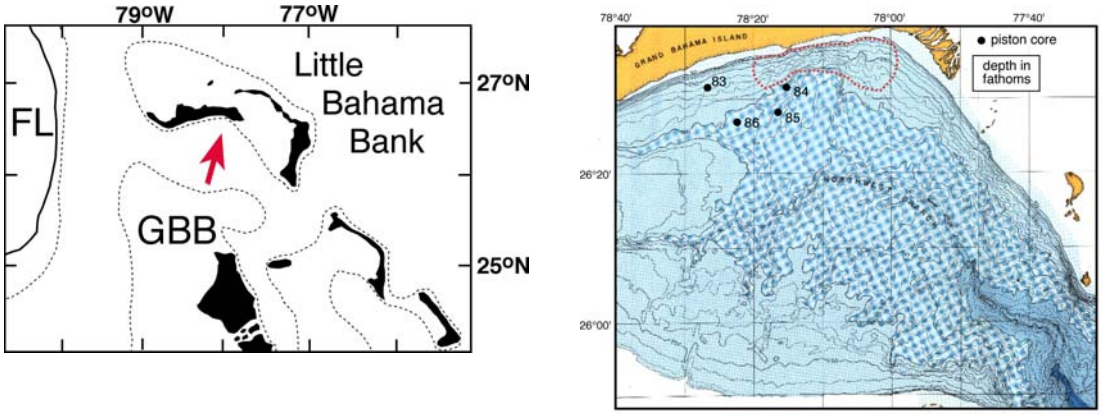

Figure 1. Location of the multi-beam bathymetry data from Little Bahama Bank (left). The area outlined in the red line represents the location of the data set.

Project Description

Bathymetric maps of the slope south of eastern Grand Bahama Island (Figure 1) will be analyzed to provide morphometrics (width, height, length) of these slope channels that range to depths of ~1000 m. These channels provide a modern analog to ancient debris-

filled channels that flank carbonate platforms, for example, along the Cretaceous Maiella platform (Eberli et al. 2000) and in the Permian Upper San Andres Formation in Last Chance Canyon.

In addition to the size aspects, we will map channel types and summarize the basic configuration (bifurcating, merging, etc) of these slope features. Many of these channels merge in a downslope direction. We will provide both dip and strike oriented transects to provide visualization of the channel morphologies. Depending on the availability of the digital data we will provide a three-dimensional rendering of the channeled slope at several vertical scales (exaggeration).

We will also develop a series of platform to basin transects in both the channeled and non-channeled parts of the slope for the purpose of assessing the influence of the larger basin configuration on channel formation. We will attempt to address specific questions regarding the influence of regional gradient (basin depth) on the channel process.

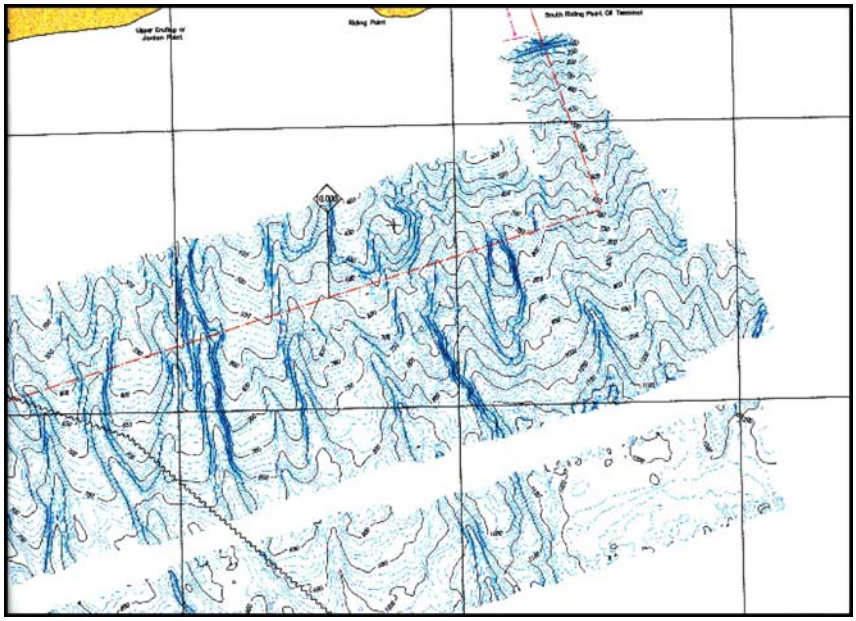

Figure 2. Analog bathymetric data from the proposed study area south of Grand Bahama Island (yellow at top of figure). The channelized slope is easily visible in these data.

Expected Results

Slope and channel data will be developed from the analog images of the slope (we are currently trying to obtain the digital data). We will quantitatively characterize the size, shape, and position of the channels and relate these data to their position along the platform as well as examine the causal relation to the deeper basin (northwest branch of the Great Bahama Canyon of Andrews et al., 1970).

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Petrophysical Characterization of Cretaceous and Tertiary Carbonate Mass Gravity Flows

Gregor Eberli, Daniel Bernoulli, Klaas Verwer, Flavio Anselmetti[1] and Rizky Sekti

[1]EAWAG, Switzerland

Project Purpose

During the previous years we evaluated the reservoir potential of Cretaceous and Tertiary breccias and calcareous turbidites along the Maiella Platform margin (Figure 1). We are in process to complement the porosity-permeability analysis with sonic velocity data and plan to test if a correlation exists between type of mass gravity flow (turbidites, slumps, breccias, etc) and their petrophysical properties. In addition, we will assess the petrophysical properties of the mass gravity flow deposits along the western side of Great Bahama Bank that were cored during ODP Leg 101 and 166 (Figure 2). This will allow a more comprehensive petrophysical characterization on calcareous mass gravity flow deposits and an evaluation of the influence of burial diagenesis on their reservoir quality.

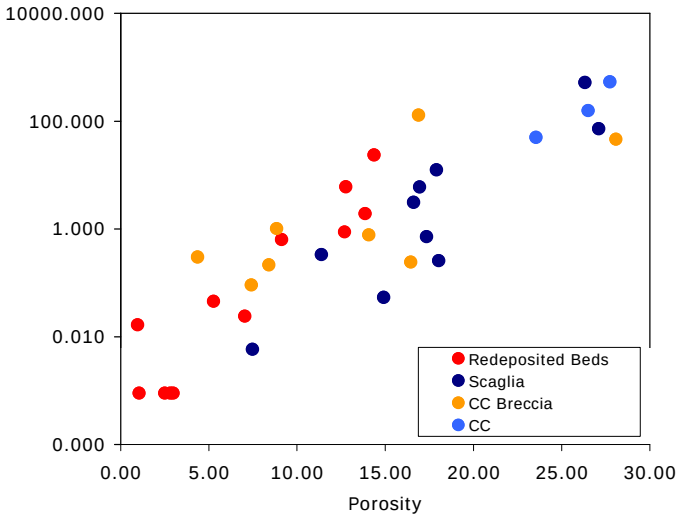

Figure 1: Porosity versus permeability of megabreccias and turbidites (red dots) and the corresponding background sediment (Scaglia, dark blue dots). Breccias rich in rudist debris (Calcare Cristallini, orange dots) have generally less porosity and permeability than the coarse-grained rudist grainstone (Calcare Cristallini, CC ,light blue dots).

Scope of Work

In the outcrop samples, we will measure sonic velocity on the same samples for which porosity and permeability data exist. A thin section will be cut from the end of each plug for analysis of, texture, pore structure, and the diagenetic paragenesis. This will allow relating pore structures to both the acoustic and hydraulic properties. The subsurface data from the seaways surrounding the Bahamas consists of seismic data, cores, logs and laboratory data (Figure 2). This will give the opportunity to describe the seismic facies of

the mass gravity flow deposits, document and compare their petrophysical properties with the more diagenetically altered rocks in the Maiella Mountains.

Key Deliverables

By combining the previously collected data set and this new data set we plan to provide a comprehensive petrophysical and diagenetic characterization of mass gravity flows along carbonate platforms.

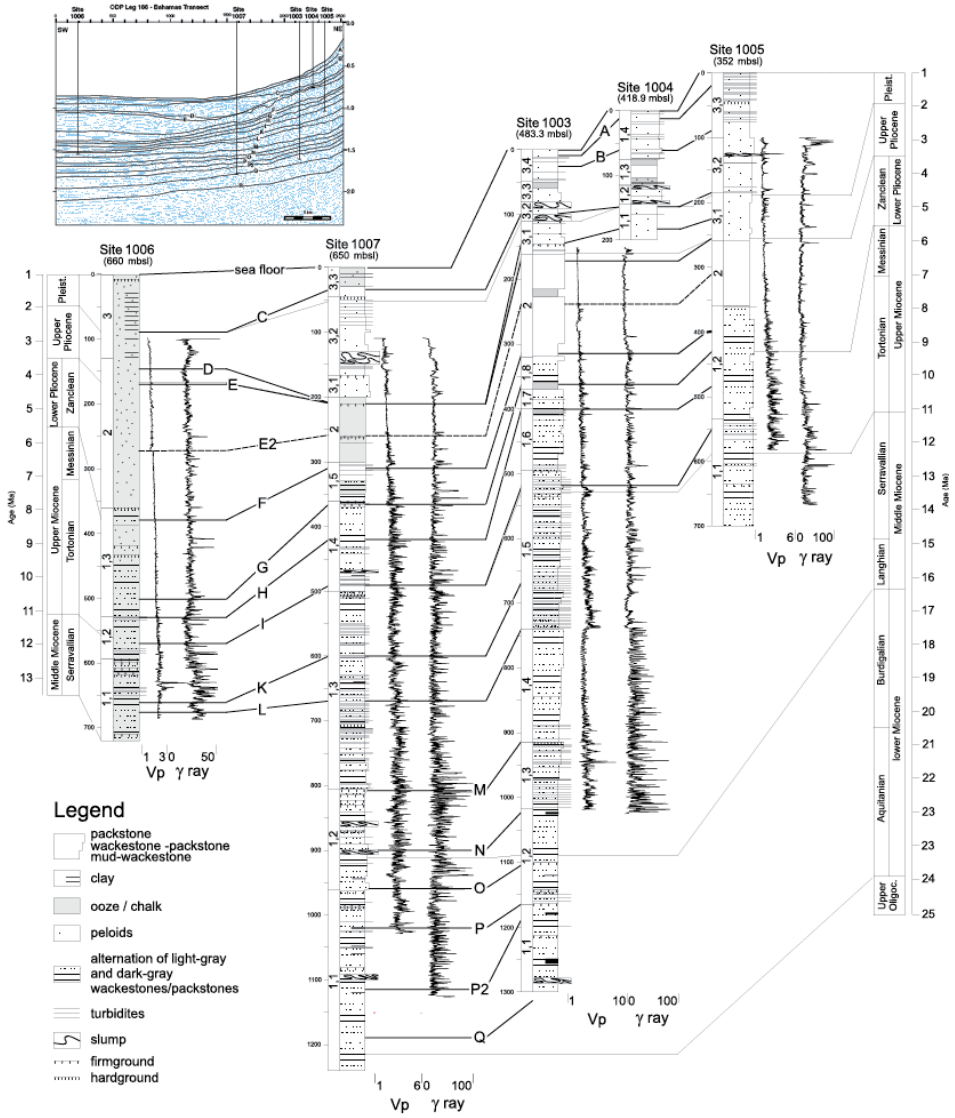

Figure 2: Lithologic, velocity and natural γ-ray log of Neogene carbonate turbidite successions along the western side of Great Bahama Bank. High velocities occur in the turbidites while the background sediments are slower.

The Origin of Carbon Isotopic Variations in Platform Derived Sediments

Peter K. Swart

Project Purpose

$\delta^{13}C$ values are widely used as a stratigraphic tool. Thus, it is important to assess whether such $\delta^{13}C$ values are being interpreted in an appropriate manner. Hence the importance of the work suggested here. In particular, this project tests the hypothesis that over the past 10 to 25 myrs, variations in the $\delta^{13}C$ of marginal platform carbonates are unrelated to changes in the relative burial of organic carbon, but rather relate to global sea-level fluctuations and reflect the relative input of carbonate with high $\delta^{13}C$ values produced in shallow water. This hypothesis will be investigated by analyzing the $\delta^{13}C$ in bulk carbonate material sampled from DSDP and ODP sites cored adjacent to modern carbonate platforms (Fig. 1).

Project Description

Preliminary data has already shown that (i) the $\delta^{13}C$ of bulk carbonate sediments retrieved from sequences of similar age, cored at sites adjacent to carbonate platforms such as Great Bahama Bank, can be correlated to each other but that these variations are unrelated to changes in the burial of organic carbon as recorded in the $\delta^{13}C$ record of open oceanic carbonates, and (ii) similar change can be recognized globally over the past 10 myrs. Although this proposal is targeted at the last 25 myrs, it clearly has implications for earlier times like the Cretaceous.

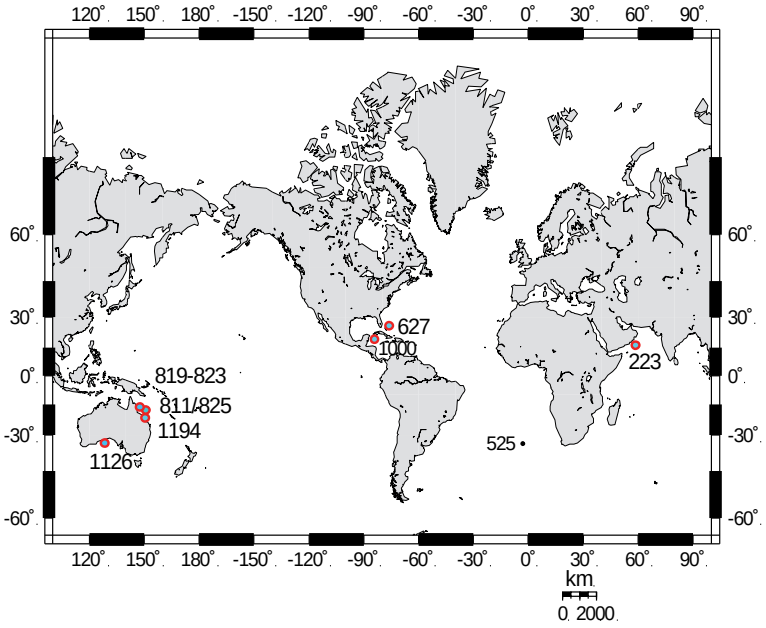

Figure 1: Locations of sites (red) from which new materials will be analyzed, for this project.

Confirmation of our hypothesis regarding the control of the $\delta^{13}C$ of sediments can be obtained to some degree by examining the timing and extent of changes across the Leg 166 sites by examining variations in the $\delta^{13}C$ during the Pleistocene-Pliocene glacio-eustatic changes in sea level. Over this interval we should see heavy values in $\delta^{13}C$ during sea level highstands and low $\delta^{13}C$ values during sea level lowstands. These differences have already been noted to some extent by previous work at other sites in the Bahamas over shorter time intervals (Droxler, 1985; Droxler and Schlager, 1985; Droxler

et al., 1983; Kroon et al., 2000) and within individual cycles (Betzler *et al.*, 1999; Reuning *et al.*, 2002).

A multiple approach is proposed which will involve the examination of the $\delta^{13}C$ of carbonates in new locations, extending the $\delta^{13}C$ record of platform derived material back in time (to at least the start of the Miocene and older if possible), examining the relationship between $\delta^{13}C$ and high-order changes in sea level, examining the corresponding changes in the $\delta^{13}C$ of organic material, and incorporating a modeling component.

Scope of Work

1) The study will use ODP and DSDP sites cores adjacent to carbonate platforms, which contain $\delta^{13}C$ records, extending back in time up to approximately 25 myrs. If possible we will extend our study further back in time but we recognize that this may not be feasible because these older strata if cored have poor recovery and are more cemented. Sites, with otentially older records include Site 627 (Little Bahama Bank drilled during ODP Leg 101), Sites 819-823 (Great Barrier Reef drilled during ODP Leg 133), Site 1000 (Nicaraguan Rise, ODP Leg 165), Sites 1194 & 1196, (Marion Plateau, ODP Leg 194), Site 1126 (Great Australian Bight, ODP Leg 182), and Site 223 drilled during the DSDP. The magnitude of the difference in the $\delta^{13}C$ between the lowstands and highstands should increase towards the platform, for examples from Sites 1005 through 1007. We will examine the timing of changes by using the $\delta^{18}O$ of foraminifera in the Pleistocene sections as a chronometer and examine how the $\delta^{13}C$ of the bulk sediment changes relative to this chronology. As sea level falls, sites closer to the platform margin should retain their positive $\delta^{13}C$ values longer than the more distal sites.
2) We will investigate the use of the $\delta^{13}C$ of organic material in the samples previously studied (Swart and Eberli, 2005). We suggest that during periods of high input from the platform, which are characterized by positive $\delta^{13}C$ value in the sediments, there will also be more organic material derived from seagrasses and macroalage. In contrast, lowstands will have organic material with more negative $\delta^{13}C$ values.

A model of theoretical changes in the $\delta^{13}C$ of periplatform sediment will be constructed, taking into account the variation introduced by the change from aragonite to calcite of shallow marine organisms (Lowenstein et al., 2003; Sandberg, 1983).

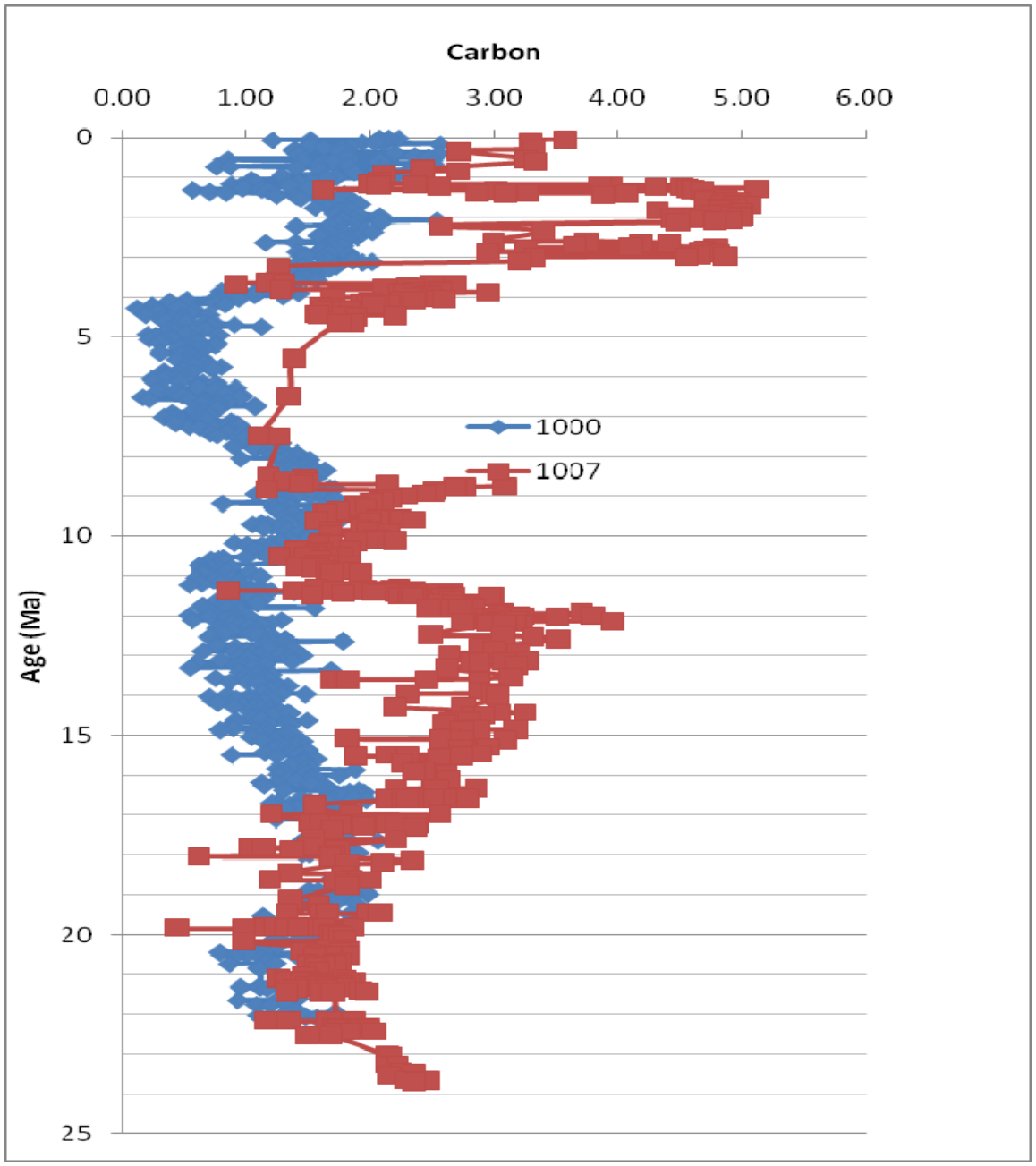

Figure 2: Comparison of carbon isotopic records from ODP Site 1000 (Nicaraguan Rise) and 1007 (Bahamas) for the last 24 myrs. Although there are some similarities there are large differences during the Middle Miocene.

Expected Results

- An understanding of how variations in the $\delta^{13}C$ of platform derived carbonates relates to variations in the oceanic $\delta^{13}C$ records. A preliminary study has recently been published, which shows that modern carbonate platforms show similar

changes in the $\delta^{13}C$ of the sediments surrounding the platforms that are not related to the global change in carbon over the same period (SWART, 2008).

- How these patterns of stable carbon isotopes are related to marine diagenesis if at all.

- An answer to the question if there are changes in the organic material, which can be used to support or negate the connection between the productivity of carbonate platforms and the carbon isotopic record?

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Mixed Carbonate-Siliciclastic Systems

Plio-Pleistocene Reef Development in the Southern Dominican Republic: Reef Growth, Facies Geometry and a Changing of the Guard

James S. Klaus, Donald F. McNeill, Gregor P. Eberli, and David Weinstein

Project Purpose

Extensive research on Holocene reef deposits has indicated that they can develop in a complex variety of ways even though the surface morphology may appear relatively simple (Figure 1). The principal factor that appears to determine the growth and facies geometries of fringing reefs is the available accommodation space and changes in relative sea level. The Pleistocene reefs that developed over the past 1.8 million years provide the best opportunity to study the complex three-dimensional architecture and controlling factors of fringing reef development during high-frequency sea level cycles. Complicating our understanding of Pleistocene reef development in the Caribbean is one the most dramatic changes in coral fauna over the past 25 million years. Miocene and Pliocene reefs of the Caribbean were dominated by species within the genus *Stylophora*. Pleistocene to modern reefs are primarily constructed by the two fast growing species *Acropora palmata* and *Acropora cervicornis*. *Stylophora* reefs may, however, be a better analog for Paleozoic and Mesozoic coral buildups. We seek to determine how the transition from *Stylophora*-dominated to *Acropora*-dominated reefs impacted fringing reef development, including changes in reef initiation, vertical accretion, progradation, and facies heterogeneity associated with the development of backreef lagoons and forereef slopes.

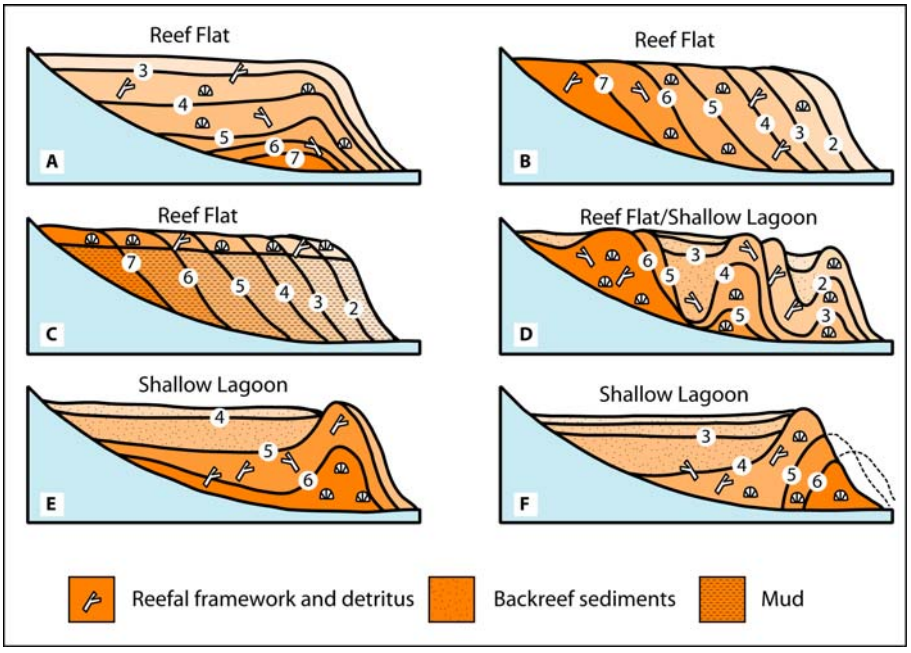

Figure 1: Generalized models of Holocene fringing reef development from Kennedy and Woodroffe (2002) showing the variation in facies geometries. Model A: vertical accretion; model B: lateral accretion; model C: lateral accretion with forereef muds; model D: episodic progradation; model E: offshore accretion with landward lagoon; model F: reef formed by offshore rubble pile.

Area and Scope of Work

The southeastern region of the Dominican Republic is characterized by an approximately 150 mile coastal plain bounded by the Cordillera Central to the west and the Cordillera Oriental to the north (Figure 2). Six to eight fairly continuous terraces are encountered in a belt of coastal reef limestones. We are initiating a two-phase integrated coring and outcrop study of the fringing reef deposits on the southern coast of the Dominican Republic. Phase I will include preliminary analysis of terrace outcrops within Santo Domingo and quarries east of the city. These analyses will consist of faunal and sedimentological characterizations as well as preliminary age determinations. Phase II (contingent upon external funding) will incorporate a transect of 10 cores taken perpendicular to the coastline within the city of Santo Domingo (Figure 3).

Key Deliverables

- Construct an integrated chronostratigraphic model for the Plio-Pleistocene reef deposits on the southern coast of the Dominican Republic.
- Reconstruct the fringing reef facies geometries, including variation vertically through the sequence as well as laterally across the southern coast.
- Determine how the transition from *Stylophora*-dominated to *Acropora*-dominated communities impacted fringing reef development, including changes in reef initiation, vertical accretion, progradation, and the development of associated backreef lagoons and forereef slopes.
- Develop an integrated model of fringing reef growth from the Pliocene to Recent including the controlling factors of sea level, tectonics, antecedent topography, and the taxonomy of dominant reef builders.
- Document the heterogeneity of reef framework versus matrix sediment and develop an associated porosity model.

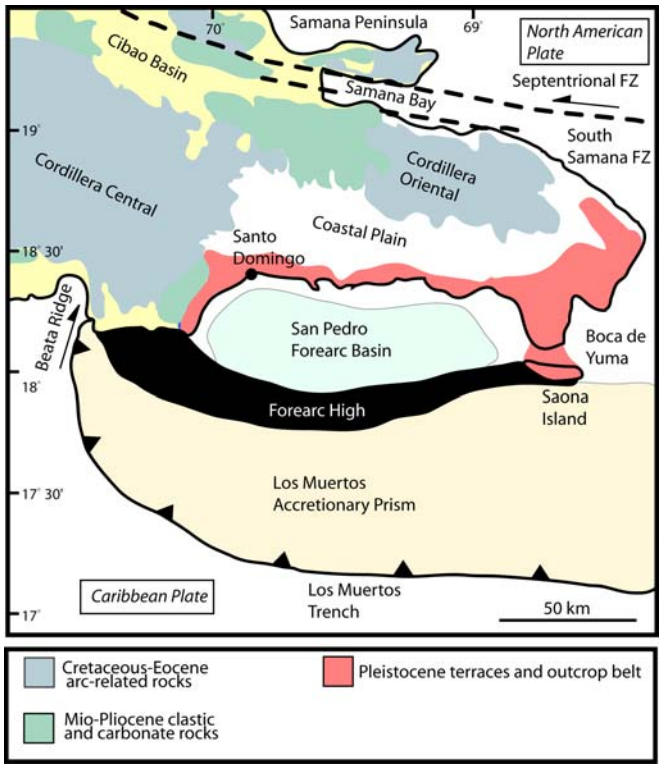

Figure 2: Geologic and tectonic map of southeastern Dominican Republic. The Pleistocene terrace and outcrop belt is shown in red. Modified from Mann et al. (1995).

Project Description

A number of scenarios can be envisioned to explain the development of the highstand reef deposits on the southern coast of the Dominican Republic (Figure 4). In the MIS-11 reef flat model (A), the broad 60 m terrace in the Santo Domingo area represents a single reef building event with a broad reef flat and back reef (~2 km). In model (B), the broad 60 m terrace is subdivided into progressively older highstand reefs which cumulatively form a broad terrace and reef flat. In model C, the base of the coastal reef deposits are similar to the *Stylophora*-dominated bedded thickets and patch reefs seen throughout the Mio-Pliocene in which large-scale reef flat development is rare (Johnson et al. 2008). By integrating core and outcrop investigations of the southern Dominican Republic we hope to unravel the three-dimensional architecture and controlling factors of fringing reef development during high frequency sea level cycles, in particular, the impact of dominant reef builders on vertical accretion rates and lateral heterogeneity of fringing reef environments.

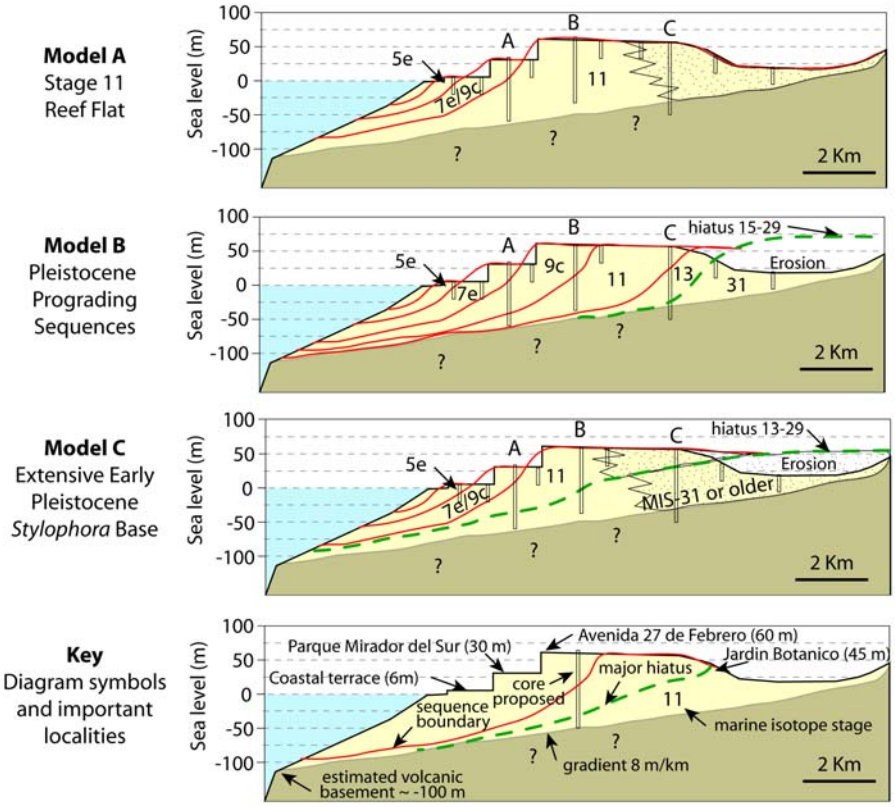

Figure 3: Cross-sectional models of Plio-Pleistocene reef development on the southern coast of the Dominican Republic.

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A Digital Atlas of the Cibao Basin Mixed System

Donald F. McNeill, James S. Klaus and Gregor P. Eberli

Project Purpose

A digital atlas of the mixed carbonate-siliciclastics (Miocene-Pliocene) of the Cibao Basin will compile our field and laboratory work over the past three years. This compilation will provide an easily accessible case study of the different types of Neogene mixing within a sequence stratigraphic framework.

Scope of Work

Data and results from this project will be compiled and presented in a HTML web-based format. The case study will be built around the four sequences that comprise the main Neogene section in the basin. We will start with regional geology and basin geometry, proceed to the sequence-scale geometries, examine the chronostratigraphy and correlation of the sequences, and provide outcrop-scale characterization of the sequences with field photographs, outcrop core borings, and other available data such as bed-specific features and thin-sections.

Key Deliverables

The digital atlas of this mixed system case study will be available through the secure CSL website as well as available to the Industrial Associates in stand-alone HTML format DVD. An overview of the atlas will be presented at the Annual Review meeting.

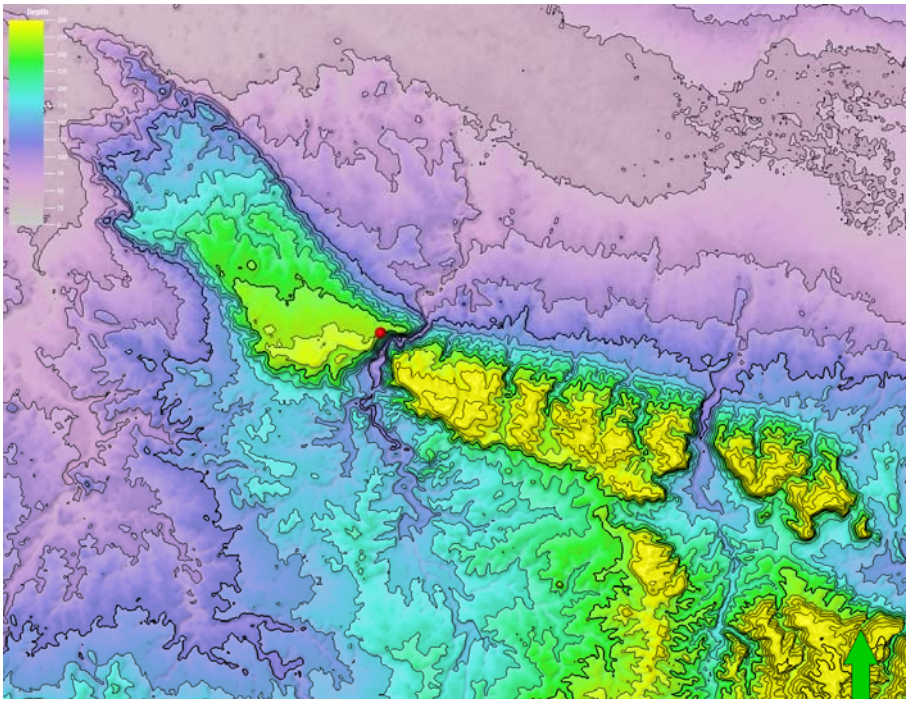

Figure 1: Digital elevation model of the prograding margin along the southern flank of the Cibao Basin, north is to the top.

Project Description

The majority of the data for this project is currently in hand with the exception of some additional outcrop cores, some additional thin-sections, and some basic lab data on mud percent (lime versus siliciclastic). The core data will be collected in March 2009 during a weeklong field visit. The key sections of the atlas will include:

1- sequence stratigraphy
2- lithostratigraphy (section, outcrop, outcrop cores)
3- faunal patterns and partitions related to the sequences
4- petrography of the mixed lithofacies
5- basin petrophysical characterization (porosity, sonic velocity)

These five sections of the atlas will be linked together with the development of a virtual fieldtrip. Each field stop will contain the full ranges of site attributes, such as the sequence stratigraphic setting, the outcrop setting, the key outcrop features, the faunal indicators, the thin-section petrography, and other relevant outcrop data (mud matrix, organic components, porosity distribution, etc.).

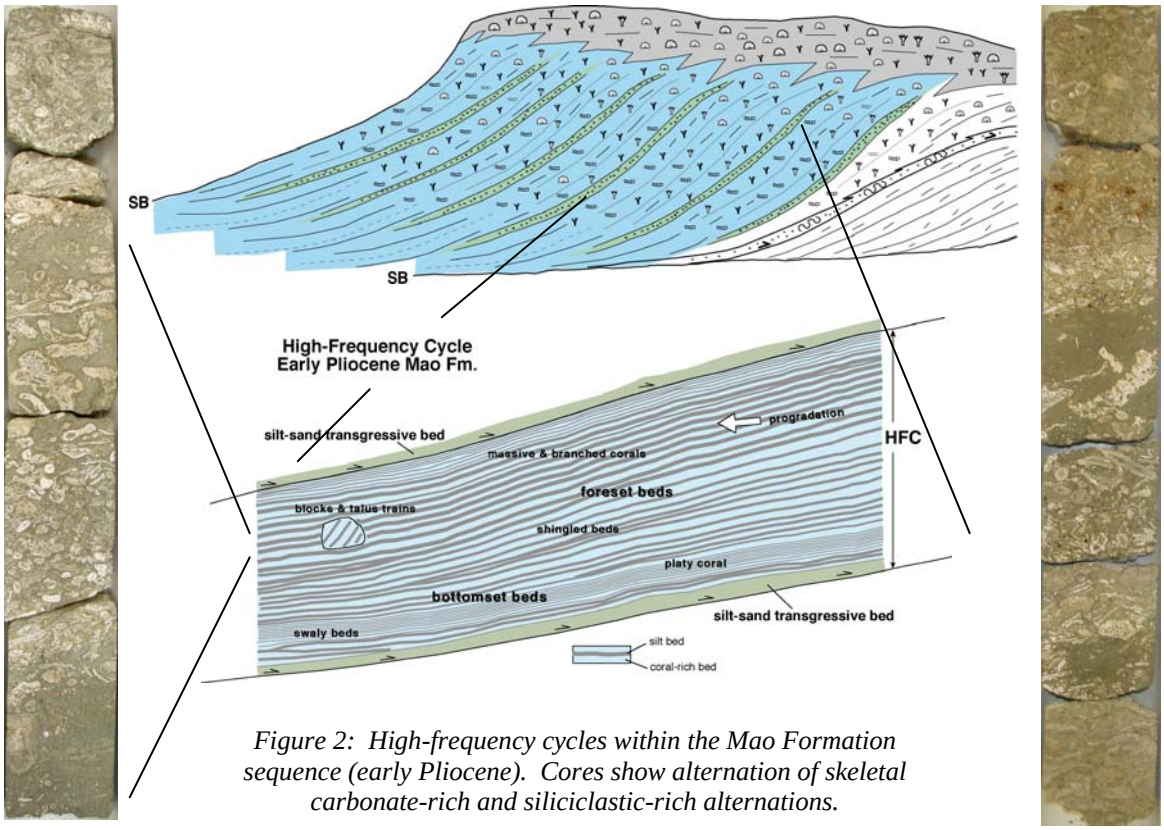

Figure 2: High-frequency cycles within the Mao Formation sequence (early Pliocene). Cores show alternation of skeletal carbonate-rich and siliciclastic-rich alternations.

Expected Results

The digital atlas will serve as the final report for the multi-year project in the Cibao Basin. The aim of this mixed system atlas is to provide a relatively young depositional analog to similar ancient lithofacies with reservoir potential.

Facies, Geometries and Sequence Stratigraphy of the Mixed Carbonate-Siliciclastic System in the Neuquén Basin (Year 1)

Michael Zeller, Klaas Verwer, Gregor Eberli, Ernesto Schwarz[1]and Luis Spaletti[1] and Jose-Luis Massaferro[2]

[1]University of La Plata, Argentina, [2]Repsol-YPF, Buenos Aires, Argentina

Project Purpose

Mixed carbonate-siliciclastic systems containing hydrocarbons pose unique problems to exploration and production because the complex variations in facies and diagenetic history result in heterogeneous reservoir properties. Optimizing field development in such an environment requires a level of reservoir characterization that adequately describes the flow networks within the reservoir as well as the variations in rock quality both laterally and vertically. The goal of the proposed research effort is to develop a predictive model of the prograding Upper Jurassic-Lower Cretaceous mixed carbonate-siliciclastic system in the Neuquén Basin.

The studied interval consists of the basinal Vaca Muerta Formation, the prograding/aggrading carbonates of the Quintuco Formation and the shelfal successions of the Loma Montosa Formation. The project will combine detailed outcrop and subsurface analysis with petrophysical laboratory measurements and state-of-the-art assessment of the pore type geometries to establish a depositional model that captures the spatial variability in depositional and diagenetic rock types, which eventually aids in enhancing the success rate in both the exploration and exploitation in mixed systems.

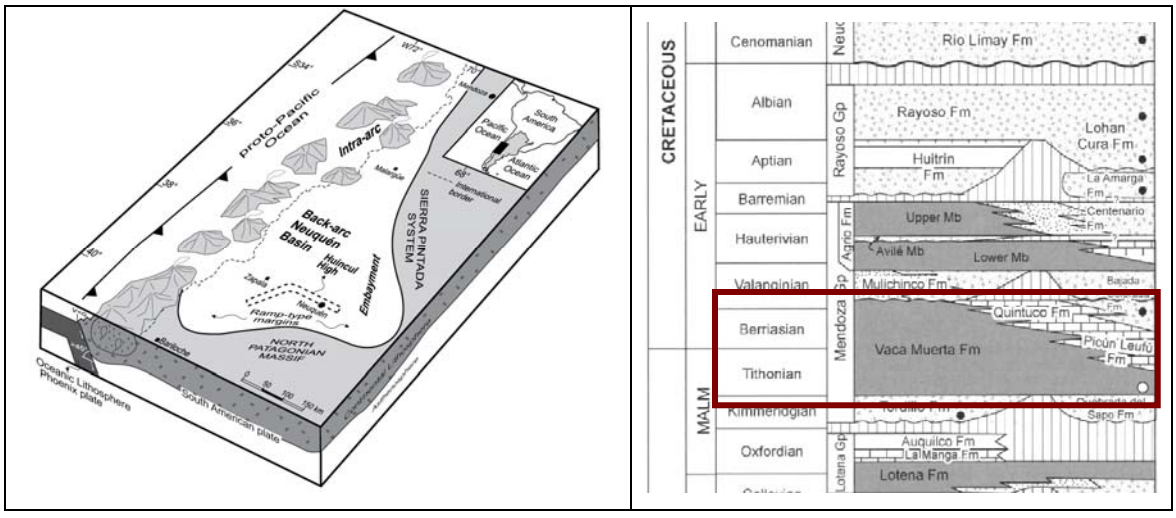

Figure 1: Left: Paleotectonic and paleogeographic location of the Neuquen Basin (modified after Schwarz et al. 2006). Right: Stratigraphic interval studied in the project (red box) (modified from Howell et al., 2005).

Scope of Work

In year 1 we will examine outcrops of Upper Jurassic to Lower Cretaceous mixed carbonate-siliciclastic system in the Neuquén Basin and assess the petrophysical properties of both outcrop and subsurface samples. A regional geologic and sequence stratigraphic framework in outcrop will be established that includes a detailed analysis of the vertical stacking patterns and lateral variability of the higher frequency cycles. The primary rationale for establishing a regional sequence stratigraphic framework is to enhance the predictability of reservoir facies and bounding flow barriers on a regional (i.e. seismic) scale. The analysis of the higher frequency cycles will constrain the reservoir-scale continuity and assess probable flow barriers. Based on the vertical stacking patterns and lateral variability observed in outcrop a comprehensive geologic model will be constructed that can be used to better understand reservoir distribution in the subsurface.

In year 2 (2010) we plan to produce a synthetic seismic model of outcrop model for a refined interpretation of the seismic data and the integration of the seismic and subsurface core and log data into a comprehensive predictive reservoir model.

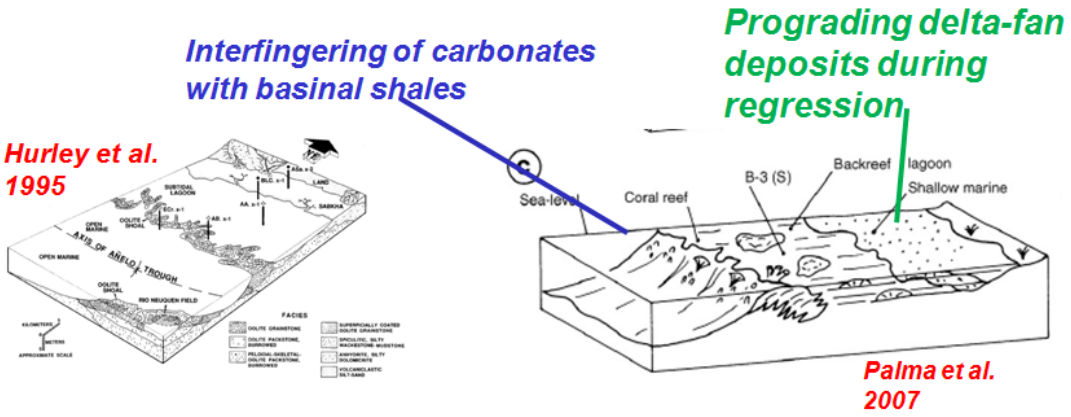

Figure 2: Depositional models of the Quintuco Formations by previous investigators. To date no integrated sequence statigraphic analysis has been conducted in this formation.

Project Description

The following tasks will be carried out:

a) Detailed logging and mapping of the Quintuco Formation and adjacent formations in outcrop.

b) Sequence stratigraphic analysis including the stacking patterns of third order and high-frequency sequences

Assessment of the lateral and vertical facies variations within the sequence stratigraphic framework and the measurement of these variations in the petrophysical properties.

c) Establishment of the scale, geometry, and heterogeneity of flow units in outcrop for correlation to the deep subsurface

d) Development of a 3-D geologic model of reservoir distribution from outcrop data that can be utilized to enhance the understanding of sedimentary processes operating

in mixed carbonate-siliciclastic environments and improve predictability of reservoir distribution in the subsurface.

Expected Results

The results of this project are expected to provide a geologic model by which the facies distribution of the reservoirs in the Jurassic and Lower Cretaceous Quintuco Formation can be predicted with a high degree of confidence. The integration of lithologic and petrophysical parameters that can be effectively correlated within the confines of an established sequence stratigraphic framework will provide a means to enhance reservoir predictability in other fields in mixed carbonate-siliciclastic environments.

Key Deliverables

This project will provide a comprehensive geological model of the Lower Cretaceous mixed carbonate-siliciclastic system in the Neuquén Basin that can be utilized to enhance the success rate in both the exploration and exploitation in similar prograding/aggrading systems.

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Petrophysical Properties of Mixed Carbonate-Siliciclastic Rocks

Klaas Verwer, Gregor P. Eberli and Filiz Afsar[1]

[1]*University of Bremen, Germany*

Project Purpose

Velocity in carbonates is largely controlled by porosity and pore types while in siliciclastic rocks the velocity is controlled by porosity, mineralogy and overburden pressure. In mixed carbonate-siliciclastic systems these controlling factors compete with each other. Few data sets exists that systematically assess the individual factors with the same methodology (eg., Anselmetti et al. 1997; et al. 1997). To close this knowledge gap we plan to undertake a comprehensive study of mixed carbonate-siliciclastic rocks. The project will utilize the newly acquired samples from the Neuquen Basin (outcrop and subsurface), the CSL database, and published literature data to assess how intrinsic factors (mineralogy, diagenesis) influence acoustic properties in mixed-carbonate siliciclastic rocks.

The findings will have implications for general prediction of lithology and pore type from acoustic data.)

Scope of Work

This project will study the acoustic behavior of mixed carbonate-siliciclastic rocks of the Lower Cretaceous Quintuco Formation from the Neuquen Basin (Argentina) and data from other locations. We will investigate and model the relation between siliciclastic material (commonly quartz of various grain size and clay minerals), carbonate matter, and porosity at effective stresses up to 30 MPa. We will document the influence of mineralogy on acoustic velocity. Second, we will assess what the effect is of postburial diagenetic alteration on the acoustic behavior. The data set could be used as an input for seismic modeling experiments and compared with subsurface analogs.

Key Deliverables

This project will provide an assessment of the exact parameters influencing acoustic properties in mixed carbonate-siliciclastic systems.

Project Description

Samples from the Neuquen field study will be analyzed in the CSL Petrophysics Laboratory to provide a comprehensive data set on mixed carbonate siliciclastic specimens. In addition, the CSL Petrophysical Database and published literature will be mined to complement the data set. The data set will aim to cover a number mixed systems with a variety of mineralogic composition and diagenetic overprint.

The resulting data will be modeled to assess the relation between siliciclastic material, carbonate matter and porosity. We will identify and model the parameters controlling the sonic velocities and assess the influence of diagenesis on the acoustic velocities.

Methodology

To quantitatively relate measurements of acoustic properties to parameters such as clay, silt, quartz, and carbonate content the following methodology will be adopted:

1. The carbonate content will be established by Thermogravimetric Analysis (TGA); the grain size distribution will be measured using a "Laser Particle Sizer," with a working range of 0.16–1400 mm to calculate the volume percentages of clay (<8 mm), silt (8–63 mm), and sand (>63 mm) (cf. Braaksma et al. 2003).

2. Ultrasonic compressional (P-wave) and shear wave (S-wave) velocities will be measured as a function of pressure (0-30 MPa) using a pulse transmission transducer arrangement (cf. Anselmetti and Eberli, 1993).

3. To display the quantitative relation between sediment composition and acoustic properties, acoustic velocity, density, and porosity will be modelled as a funtion of their composition. For the mixed carbonate-siliciclastic samples the relationships will be investigated using ternary diagrams (Fig. 1; cf. Braaksma et al. 2003). The pure carbonate samples will be assessed using digital image analysis to measure pore shape parameters which will be quantitatively related to Sun's Extended Biot Theory (Fig. 1; Weger et al., In press).

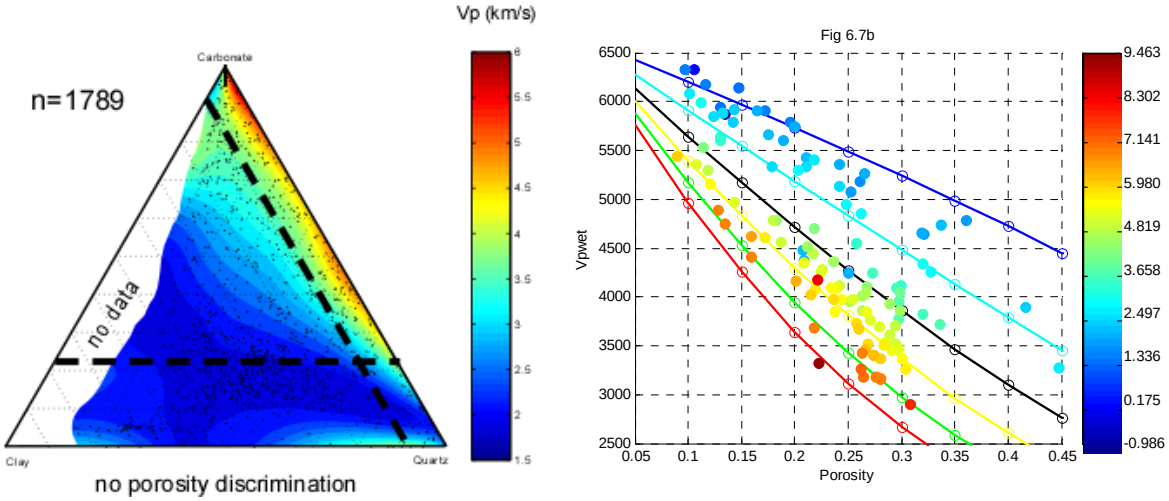

Figure 1: Example ternary diagram showing the relationships between P-wave velocity and textural and mineralogical composition (from Kenter et al. 2007) (left); Cross plot of porosity vs. P-wave velocity with the gammaK parameter from Sun's Extended Biot Theory superimposed. The gammaK parameter captures the frame flexibility at a given porosity and provides a mean to relate the pore structure of carbonate rocks to acoustic velocity variations (Weger et al. In press).

Expected Results

The findings will shed light on the significantly more complex acoustic behavior in mixed carbonate-siliclastic sedimentary rocks than in pure siliciclastics where mineralogic composition explains most of the observed relationships between porosity

and sonic velocity, and pure carbonate in which pore structure is accounted for explaining variation in acoustic velocity at a given porosity.

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Fundamental Research

The Role of Early Cements in Maintaining Porosity and Permeability during Burial: Compaction Experiments

Rosely de Araujo Marçal, Gregor P. Eberli and Antonio Claudio Soares[1]

[1]*Petrobras Research Center, Rio de Janeiro, Brazil*

Project Purpose

Early diagenesis usually strongly influences the early distribution of porosity and permeability but it is not known how the early cements resist compaction and how the increase of burial depth affects porosity and permeability in carbonates. To close this knowledge gap we plan compaction experiments of modern sediments and Pleistocene samples with different amounts of cementation to assess the decrease of the initial porosity and permeability at different burial depths. The results will provide much needed information on the factors that maintain porosity and permeability in the deep burial realm.

Project Description

This project will examine the influence of the amount of early cementation as a factor in sustaining porosity and permeability at deep burial depths. Compaction experiments will simulate the evolution of permeability from the surface to the equivalent of 3,000 meters of burial depth. We will use Pleistocene oolitic grainstones and peloidal packstones from Great Bahama Bank. Porosity and permeability will be measured and in each sample the

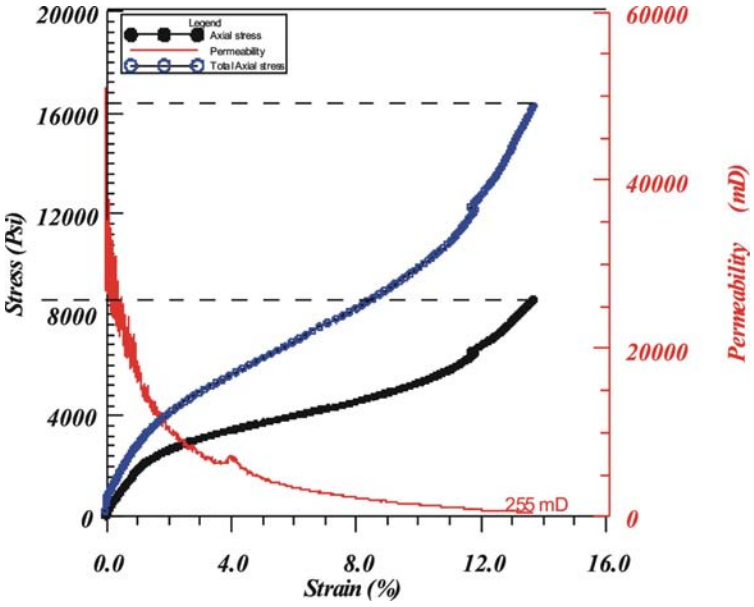

Figure 1: Stress versus strain and permeability of an ooid sample. Permeability (thin red line) abruptly increases at 4% of strain, which is probably caused by micro-fractures that start to develop. The decreasing permeability with increasing stress indicates that these micro-fractures close with increasing burial.

amount and distribution of cementation/dissolution will be quantified using petrography. We will simulate different burial depths in these samples starting with their initial porosity and permeability values, and then monitor their decreasing values as compaction increases, which we equate to the increase of burial depth. After the experiments, thin sections will be cut from each sample, we will measure the capillary pressure using Hg injection (P_{Hg}) and perform microtomography. Combined these post experiment investigations will help to evaluate the main changes of the distribution and shape of the pores. The geomechanical experiments will be done at Rock Mechanics Laboratory at Petrobras Research Center with a MTS 315.02, an axial compression of 270 Tf power and 12000 psi of confining pressure.

Example Results

We started the experiments using sediments (ooids with no cementation) in order to simulate burial of ooids with no cementation. Pressure was increased from zero until the equivalent to 2,830 meters of burial depth (8,500 psi/58.6 MPa). The main decrease in permeability occurred at 4% of strain which was probably caused by a rearrangement of the grains. Subsequently a new framework stability is achieved. Permeability increased by a small amount, which is attributed to closure at micro-fissures clearly increasing pressure. At the end of the experiment, the facies still shows 255 mD of permeability.

Significance

The results of these experiments will show how early cementation influences the petrophysical properties during burial. Our working hypothesis is that this is the main factor for sustaining the reservoir quality porosity and permeability at great depth. This knowledge is important for assessing reservoir quality in new exploration plays. In addition it will create a database that we can compare with databases from different burial depths, in order to improve modeling reservoirs.

The Influence of Interparticle versus Vuggy Porosity on Acoustic Velocity of Carbonates

Gregor P. Eberli, Klaas Verwer and Mark Knackstedt

Project Purpose

1) To disprove the common assumption that carbonates with moldic and vuggy pore types principally display higher acoustic velocity than rocks with predominantly inter-crystalline/inter-particle porosity at equal total porosity. This assumption has been used to quantitatively estimate the amount of secondary porosity and separate-vug porosity by modeling porosity from acoustic logs (e.g. Schlumberger, 1974, Nurmi, 1984; Lucia and Conti, 1987; Wang and Lucia, 1993). New data question this assumption and indicate that rocks with inter-particle pore types also can display high acoustic velocity for a given porosity (Fig. 1). This would have implications for log and seismic-based porosity estimates.

2) To identify the processes, which stiffen the rock to achieve high acoustic velocity. The working hypothesis is that in vuggy rocks the stiff framework is produced mainly by the bulk of the rock encapsulating the vugs, while in rocks with inter-particle porosity contact cements weld the grains together to form a stiff and fast rock.

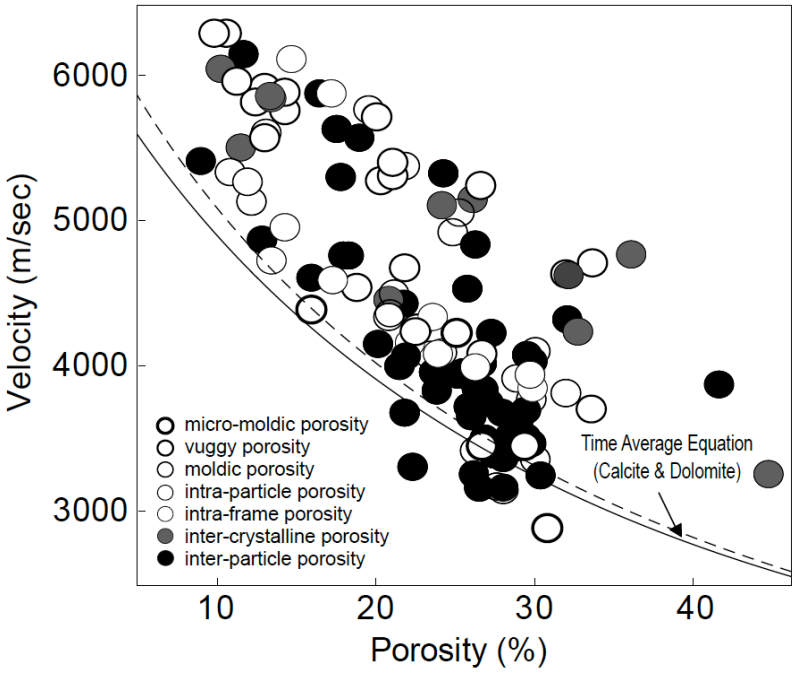

Figure 1: Velocity-porosity cross-plot of samples measured at 20 MPa with annotation of porosity types separated into two groups. Open circles are samples with vuggy/moldic and intra-frame/grain porosity, black and grey dots represent samples with inter-particle and inter-crystalline porosity. A large overlap exists between these two groups, indicating that rocks with inter-particle/inter-crystalline porosity can in some cases have a stiff framework and high velocity (from Weger et al., submitted AAPG Bulletin).

Scope of Work

The acoustic velocities, porosities and permeability of carbonates containing the two end-member pore types (vuggy/moldic and intergrain/intercrystalline) will be measured to assess the velocity-porosity transforms of rocks with these pore types. In addition, digital image analysis will be performed on thin sections from all measured samples to quantitatively describe and relate pore geometry to the petrophysical data. Furthermore, the diagenesis of each sample will be investigated using microscopy and SEM. Finally, high-resolution CT scans will be acquired of a selected number of samples. The 3D image data will be used to derive directly acoustic velocity vs. porosity, pore connectivity and porosity-permeability relationships via numerical simulation and compared with measured data on the same rock. This last task will be done in collaboration with the Center for Applied Mathematics, Australian National University in Canberra.

Project Description

It is well known that carbonate rocks with vuggy and moldic pores have high acoustic velocity at a given porosity but such high velocity is less often documented for rocks with interparticle and intercrystalline pores. Permeability is usually low in rocks with vuggy porosity (Lucia, 1995) but is high in rocks with intergrain/intercrystalline porosity irrespective of the acoustic velocity. Intervals where rocks with interparticle porosity have high velocity will produce a positive acoustic impedance but will not be tight, low porosity sequences and potentially contain high permeability.

Macro-porosity can be ineffective (in regards to velocity) if the solid frame around the pores carries the acoustic wave. The processes that form frame stiffening in rocks with inter-crystalline porosity vary. For example, Dvorkin and Nur (1996) document how contact cementation explains high velocity in high-porosity sandstones from the North Sea. In carbonates, early cementation often takes place at grain contacts as meniscus cements derived from meteoric waters in the vadose environment (Harris, 1978; Longman, 1980) or as micritic bridging cements in the marine realm (Figure 2). Even

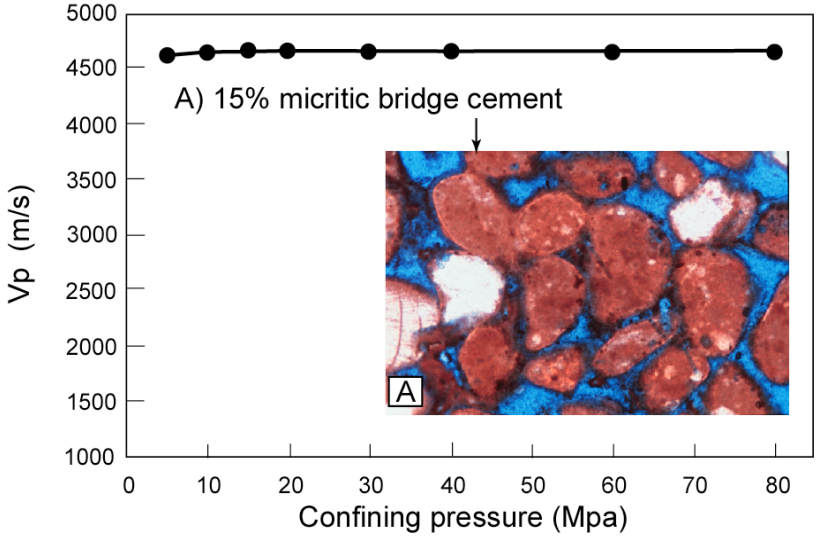

Figure 2: A modern peloidal grainstone with interparticle porosity (and microporosity within the grains) displays a high-velocity under confining pressures from 5 – 80 MPa. 15% of micritic bridging cement stiffens the rock to produce this high velocity.

small amounts of such bridging cement at grain contacts stiffens the rock dramatically to produce a high velocity. In dolomites interlocking of crystals might increase dramatically acoustic velocity because isolated rhombohedra grow together to form a stiff framework. The goals of this project are twofold; first to document that high-velocity rocks with intergrain porosity are more common than previously thought and, secondly, to document the processes that produces these high-velocities.

Key Deliverables

A data set of carbonates with high velocity but contrasting pore-types will be assembled and related to their permeability and digital image analysis parameters. The processes that produce high velocity from these contrasting pore types will be explained with a diagenetic analysis and high-resolution CT-scans and modeling.

Expected Results

The results are expected to prove that not only separate-vug porosity is ineffective for sonic velocity but also large intergrain porosity. These findings will explain why log-based porosity estimates are not always successful.

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Vp/Vs Ratio in Carbonates

Klaas Verwer and Gregor P. Eberli

Project Purpose

The compressional to shear wave velocity ratio (Vp/Vs) is an important parameter in seismic amplitude versus offset (AVO) analysis, and has been claimed to provide lithologic information (Wilkens et al., 1984) and pore fluid and pore pressure information (Duffaut and Landro, 2007; Rojas, 2008). Based on the assumption that the pore structure influences the Vp and Vs differently, its ratio has been used to extract various rock properties from the Vp/Vs ratio. There is, however, no established correlation between the pore structure and Vp/Vs ratio. Nonetheless, the ratio of P-wave over S-wave velocity, as the ratio of longitudinal over transverse strain, should relate to the speed of propagation and reflection of stress waves and as such be important in predicting the nature of rocks (Rafavich et al., 1984).

The project will utilize the CSL database petrophysical laboratory measurements to assess how intrinsic factors (mineralogy, pore shape parameters) and extrinsic factors (saturation type, pressure) influence Vp/Vs ratio. The findings will have implications for amplitude versus offset techniques and general prediction of lithology and type from acoustic data.

Scope of Work

Previous years CSL has investigated how intrinsic and extrinsic factors control Vp/Vs ratio in carbonates. This has led to findings in particular around extrinsic parameters such as pressure and saturation type. No intrinsic parameters, such as pore type, however, have been identified. In addition, it was shown that Vp/Vs ratio proved to be non-constant with porosity. This is of significance as many rock physics modeling theories assume that the decrease in Vp with increasing porosity is equal to the decrease in Vs and as a result the Vp/Vs ratio remains constant with porosity.

This project evaluates how intrinsic factors influence Vp/Vs ration in carbonate rocks. Digital image analysis (DIA) parameters will be correlated with measurements of acoustic properties. The relationship between intrinsic parameters and Vp/Vs ratio will be incorporated and tested in Sun's Extended Biot Theory.

Key Deliverables

This project will provide an overview of the factors controlling Vp/Vs ratio in carbonates. Results will be presented at the Annual Review and images and data made available to the Industrial Associates.

Project Description

The project will utilize the following workflow:

1. Mine CSL Petrophysics database for Vp/Vs, density and porosity data at identical effective pressure steps, fluid saturation and availability of DIA parameters from thin sections.

2. Evaluate scatter in acoustic measurements of Vp/Vs ratio as a function of intrinsic and extrinsic parameters.
3. Incorporate obtained relationships between Vp/Vs ratio and parameters within Sun's Extended Biot Theory.

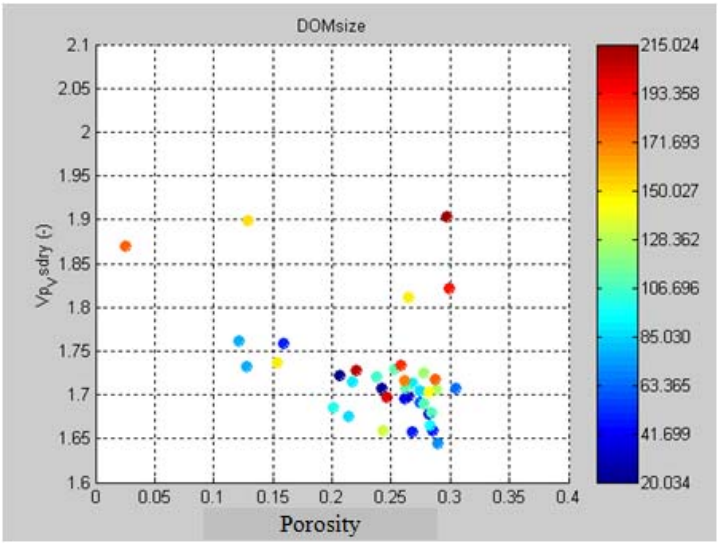

Figure 1: Cross plot of porosity and Vp/Vs ratio for a sample set of dry measurements from a Middle Eastern limestone reservoir. Superimposed is the digital image analysis parameter Dominant Poresize (in microns). No clear relationship is visible between pores structure data and Vp/Vs ratio. Vp/Vs ratio shows a negative correlation with increasing porosity, indicating that Vp/Vs ratio is non-constant with porosity.

Expected Results

It is recognized that the relationship between intrinsic parameters, such as pore structure, and Vp/Vs ratio is difficult to establish. The project aims to further explore the usability of Vp/Vs ratio as a pore structure discriminator in carbonate rocks. Expected results will include an inventory of parameters influencing Vp/Vs ratio and implications of a non-constant Vp/Vs ratio with porosity in rock physics models.

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Sulfur Isotopic Composition as a Tool in the Understanding of Diagenetic Carbonates

Peter K. Swart and Samantha Evans

Project Purpose

The issue of carbonate associated sulfate (CAS), or sulfur trapped within the matrix of carbonate minerals (Figure 1), has attracted a significant deal of attention because of the possibility of utilizing this source of sulfur to refine the oceanic sulfur isotopic curve which at present is based mainly on the analysis of evaporite minerals (Burdett, 1990). This project is designed to investigate the use of the stable isotopes of sulfur (^{32}S and ^{34}S) in carbonate associated sulfate (CAS) as possible diagenetic tools to understand the paragenesis of certain carbonates such as high-temperature related carbonates and dolomites.

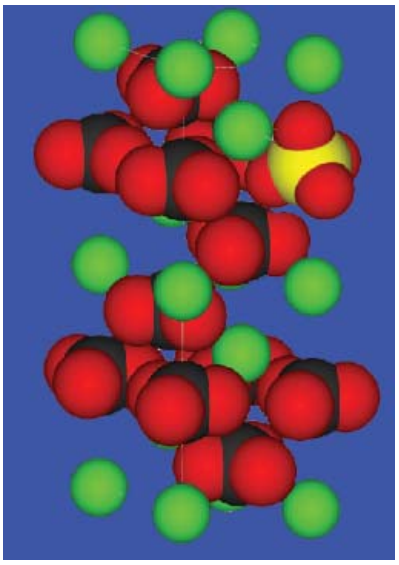

Figure 1: Schematic diagram showing the substitution of a sulfate ion for a carbonate ion in the calcium carbonate structure.

Scope of Work

Initially the equipment necessary to process the samples was developed for the stable S isotopic analyses, and in 2008 we completed changes to the instrument and now are ready to start analyzing samples. For a preliminary test of the method we have prepared samples from several ODP sites where the sediments were originally deposited under open marine conditions, but are now bathed in fluids with quite different concentrations of sulfate, both much higher and much lower. Using cleaning techniques developed over the past year we are removing the sulfate from these samples and analyzing concentration of the carbonate associated sulfate.

Key Deliverables

We hope to be able to use the $\delta^{34}S$ of CAS to ascertain the nature of the diagenetic environment, i.e. open marine, closed marine, sulfate reduction, and thermo-chemical sulfate reduction.

Project Description

In addition to obtaining the $\delta^{34}S$ of the original depositional seawater, the $\delta^{34}S$ can provide information in conjunction with the concentration of non-conventional trace elements (S, Na, K, and Cl) regarding the nature of the environment of diagenesis. For example, it is well known that many dolomites are formed within the sulfate reduction zone, where dolomitization is promoted by the degradation of organic material (creating alkalinity) and perhaps by the removal of the inhibitory sulfate ion (Baker and Kastner, 1981). Such dolomite would have lower concentrations of S, normal concentrations of Na, K, and Cl, but slightly elevated $\delta^{34}S$ values. In this environment the concentration of

sulfate would be expected to be lower than in normal marine sediment and the $\delta^{34}S$ would be slightly enriched as the process of sulfate reduction forms H_2S depleted in $\delta^{34}S$ (Goldhaber and Kaplan, 1975) thereby enriching the residual sulfate. Dolomites associated with evaporite minerals might have low concentrations of SO_4^{2-} (as SO_4^{2-} is removed during the formation of evaporite minerals), normal $\delta^{34}S$ values, but elevated values of Na^+, K^+, and Cl^-. Dolomites formed from brines, which have not attained saturation with respect to gypsum or anhydrite might be expected to show elevated concentrations of all non-conventional trace elements including sulfate and normal $\delta^{34}S$ values.

Expected Results

Our results will enable us to ascertain whether the $\delta^{34}S$ of CAS can provide important information on the diagenetic environment of carbonate diagenesis including the environment in which dolomites are formed.

References

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CSL Field Seminars

Field Seminar

Sequence Stratigraphy and Reservoir Distribution in a Modern Carbonate Platform, Bahamas

AAPG seminar

Leaders: Gregor P. Eberli, G. Michael Grammer, and Paul M. (Mitch) Harris

Date: June 15-20, 2009

Location: Begins and ends in Miami, Florida. Four days are spent on a chartered boat in the Bahamas. Flights to and from the Bahamas, all ground transportation, boat, accommodation in the Bahamas, meals, and course notes are included in the tuition.

Who Should Attend: Petroleum geologists, geophysicists and reservoir engineers who are working in carbonates and need to understand facies heterogeneities and porosity distribution on exploration and production scales.

Corals offshore Andros Island

Getting ready to explore the platform

Objectives and Content

This seminar consists of a core workshop (1 day) combined with the examination of modern and Pleistocene deposits on Great Bahama Bank (5 days). This combination of subsurface data and modern and ancient deposits helps to

illustrate the vertical and horizontal variability of facies and rock properties in carbonate platform reservoirs. Cores from a seven hole transect from Great Bahama Bank to the deep-water areas in the Straits of Florida (Bahamas Transect) provide a unique opportunity to assess the sequence stratigraphic distribution of facies and diagenetic modification in platform carbonate reservoirs. Log and laboratory data from these wells calibrate the rock properties and provide insights into porosity/velocity relationships and permeability in platform carbonates.

As modern analogs, the facies belts on Great Bahama Bank display the depositional heterogeneities that could occur in ancient hydrocarbon reservoirs. We explore the spatial heterogeneity within a carbonate platform, a facies belt or individual facies bodies, while simultaneously exploring the fundamental controlling processes. In particular, sedimentary structures, dimensions and lateral variability of classic reservoir facies are examined during the seminar. Pleistocene outcrops on Bahamian islands show how these facies are preserved in the ancient rock record. The goals of the seminar are (1) to illustrate the processes that produce heterogeneities in carbonates, (2) to improve the interpretation of subsurface data sets of carbonate systems and (3) to outline solutions for the construction of carbonate reservoir models.

Tuition: $3,850

Registration at AAPG: http://www.aapg.org/education/fieldseminars/details.cfm?ID=4

or by phone 1-800-364-2274

Leaders: Gregor P. Eberli, G. Michael Grammer, Paul M. (Mitch) Harris

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Paul M. (Mitch) Harris Chevron Energy Technology Company 6001 Bollinger Canyon Road, Room D-1212 San Ramon, CA 94583-2324	Phone (925) 842-4336 Fax (925) 842-2076 Email MitchHarris@Chevron.com

Field Seminar

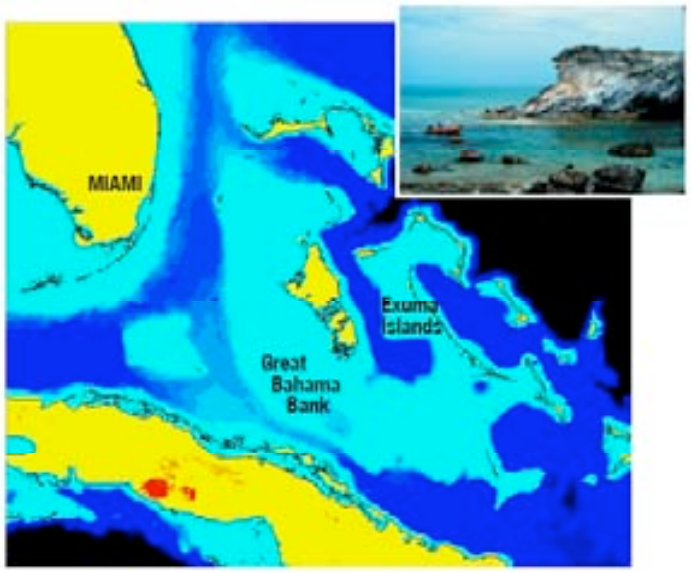
Heterogeneity of Bank-Margin Ooid Sands
Depositional Models and Reservoir Analogs
Exuma, Bahamas

Open seminar for Industrial Associates of the Comparative Sedimentology Laboratory, University of Miami

Leaders: Gregor P. Eberli, Donald F. McNeill and Paul M. (Mitch) Harris

Date: June 21-26, 2008

Location: Begins and ends in **Nassau, Bahamas**. Five days are spent on a chartered boat in the Exuma Islands, Bahamas. We will visit by boat 14 different settings illustrating the various environments along the windward margin.

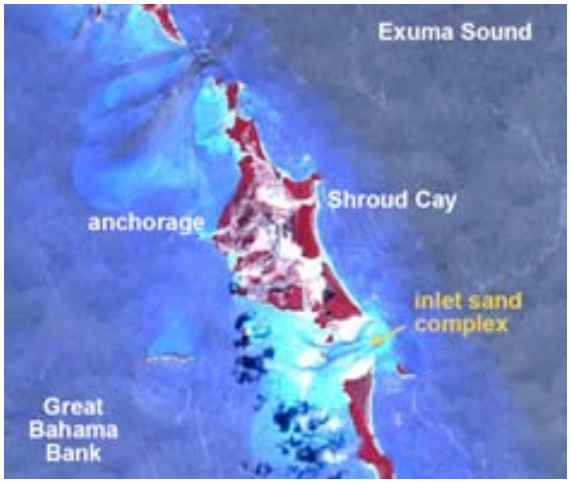


Objectives and Content

The Exuma island chain is an ideal place to study the facies relationships and heterogeneity of a grainstone dominated, high-energy carbonate platform margin. The main objectives of the seminar are a) to illustrate the dimension of the large-scale exploration-scale facies belts of such a margin, and b) to examine the smaller, reservoir-scale heterogeneity within these facies belts.

To reach these goals we will examine the vertical-lateral juxtaposition of bank-margin lithofacies and the early diagenesis in these facies. In particular, we will study the accumulation of sand in tidal channel and tidal deltas and examine the various sub-environments with differing grain-composition and sedimentary structures. Karstified eolian islands dunes and Pleistocene outcrops will illustrate the influence of meteoric diagenesis on the bank margin deposits. The islands will also serve as overview points for viewing the dimensions of the various environments. Reefs and modern stromatolites in normal, open marine environment and subtidal tidal passes will demonstrate the reef building communities in these high-energy environments. In short, the seminar will document the exploration-scale facies relationships as well as reservoir-scale features in an ooid complex, the spatial distribution of sand sub-environments, disconformities, sub-aerial exposure horizons, and the internal structure, cementation, porosity of eolianites.

Grainy ooid tidal channel of Shroud Cay



Shroud Cay ooid tidal complex

Tuition: $3,500.-, All ground transportation, boat, meals, course notes with virtual field seminar CD are included in the tuition.

Registration: kneher@rsmas.miami.edu, (305) 421 46 78,
Comparative Sedimentology Laboratory, 4600 Rickenbacker Causeway, Miami, FL 33149, USA

Leaders: Gregor P. Eberli, Donald F. McNeill, and Paul M. (Mitch) Harris

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