Comparative Sedimentology Laboratory

Rosenstiel School of Marine and Atmospheric Science
University of Miami

2010
Research Program Prospectus

CSL
University of Miami

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Mission of the Comparative Sedimentology Laboratory

The mission of the Comparative Sedimentology Laboratory (CSL) is to conduct fundamental science for improved carbonate reservoir prediction and characterization.

To fulfill this mission we perform multidisciplinary research in geology, geophysics, petrophysics, diagenesis and geochemistry of carbonates by integrating fieldwork, laboratory experiments and theoretical studies. In many projects several aspects are applied to reach the research goals. In 2010 we will focus on four main themes:

- Carbonate Systems and Reservoir Characterization
- 3D Visualization of Fractures, Karst and Fluid Flow
- Laboratory Experiments in Petrophysics
- Exploration of New Geochemical Tools

Twenty individual projects investigate various aspects of these themes. They 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, and publications. Knowledge transfer is also offered in field seminars and short courses as continuing education for geoscientists in 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.

In 2010 we offer two **field seminars** to the Bahamas to our Industrial Associates. They are a unique opportunity to learn and/or enhance the knowledge of carbonate systems and exploration and production-scale heterogeneities. The content and cost 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 short courses in carbonate seismic stratigraphy and facies analysis, geochemistry, petrophysics or trips to the mixed systems of Belize, the Dominican Republic or the Paradox Basin, the Cretaceous Maiella Platform, Italy, 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.

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James S. Klaus, Ph.D. 2005, University of Illinois
Evolution and extinction of Cenozoic to Recent reef corals, paleoecology of Cenozoic reefs, geomicrobiology of modern coral reef ecosystems.

Donald F. McNeill, Ph.D. 1989, University of Miami/RSMAS
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2010 Research Focus

The 2010 focus within the **Carbonate Systems and Reservoir Characterization projects** is on assessing the stratigraphic heterogeneity that is created by high-frequency sea level changes. Shallow-water carbonates contain mostly the record of the sea level highstands, which as new research indicates were not always stable but fluctuated in the order of 5 – 15 meters. This instability coupled with variable amplitudes of successive sea level fluctuations produce a complicated stratigraphic record. On New Providence Island (one of our study sites) it produces a complex patchwork of facies of different ages. Along the windward margin in the Exumas (Bahamas) highstand variability is recorded in stacked successions of shallow-water carbonates. To comprehensively assess the margin stratigraphy and heterogeneity we plan to map the modern facies heterogeneity using satellite imagery compared to ground-truthed bathymetry and sediment samples while the vertical stratigraphy will be assessed in core borings through the Pleistocene sequences. In a similar approach we investigate the reef successions of Glovers Reef in Belize where coral assemblages will provide additional information about environmental changes during sea level highstands. In a project in outcrops on the southern coast of the Dominican Republic we will study the complex three-dimensional architecture and controlling factors of fringing reef development during high frequency sea level cycles. This project aims to characterize the composition, morphology and distribution of fringing reefs. All these studies will be conducted in conjunction with the petrophysical characterization of the stratigraphic heterogeneity. Such a characterization is completed in the second outcrop study in the Nequen Basin (Argentina) in the prograding Upper Jurassic-Lower Cretaceous mixed carbonate-siliciclastic system. This year's effort will concentrate on the subsurface analysis and the correlation to the outcrop depositional model that captures the spatial variability in depositional and diagenetic rock types.

Some projects in the deep-water depositional environment will be completed in 2010. For example, the first phase of the comprehensive assessment of the relationship between deep-water coral mound morphology and antecedent topography, current strength and variations in the amount off-bank sediment will be complemented with a quantitative habitat characterization. A geochemical analysis, using stable carbon and oxygen isotopes and trace and minor elements of drilled deep-sea coral skeletons will also be completed. 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 Myrs, variations in the $\delta^{13}C$ of platform carbonates are unrelated to changes in the relative burial of organic carbon, but rather relate to global sea-level fluctuations. In particular the project aims to produce the records of $\delta^{13}C$ of the organic material from the late Oligocene to the recent past in four cores to evaluate spatial variations in the carbon isotopic records, as well as to assess the validity of calculating pCO_2 from the difference between organic and inorganic carbon fractions.

We are in contact with German scientists for a new phase of research on deep-water coral mounds. We are excited that a collaborative project with French scientists (Mulder and Borgomano) characterizing the morphology and geometry of carbonate mass gravity flows along the slopes of the Great and Little Bahama Banks. A 27 day seismic and coring cruise (CARAMBAR) is scheduled for November of 2010.

3D Visualization of Fractures, Karst and Fluid Flow with Ground Penetrating Radar continues to be a major focus in our research effort in carbonate reservoir characterization. In the late Barremian strata in the Solvay quarry in Cassis (France) we combined outcrop, Lidar and GPR data to assess the formation and 3D distribution of solution-enhanced fractures. This year we concentrate on the associated karst to reveal its 3D connectivity and relationship to the fracture network. At Madonna dell Mazza quarry in Maiella Mountains (Italy) where porous Upper Cretaceous rocks contain abundant deformation bands, we successfully performed time-lapse GPR experiments to detect and quantify fluid flow. A total of 105 combinations of pairs of repeated surveys can be used to calculate intrinsic time shifts and track flow with time increments between 2 hours and several days. The analyses of all these volumes will enable us to calculate flow propagation rates within porous matrix and to quantify influence of faults and deformation bands on flow. In addition, a flow simulation is planned using the 3D GPR volume as input for a comparison of water content change volumes observed in the GPR data and calculated in the simulation. 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 new equipment NER Aurolab 1000 is used for most **Laboratory Experiments in Petrophysics.** Several experiments revolve around the controlling factors for acoustic velocity in carbonates. While we continue to investigate the influence of the pore structure on velocity, we expand these investigations by relating the pore structure to diagenesis in order to answer questions of how reservoir quality porosity can be preserved. Samples from reservoirs offshore Brazil will be used for this assessment. Samples from the coring and sampling in the Exumas, Glovers and the Dominican Republic will relate stratigraphic heterogeneity to petrophysical variability. The new equipment also enables us to investigate the effects of the pore structure on the electrical resistivity of carbonates.

New equipment in the Stable Isotope Laboratory has opened new opportunities for **Exploration of New Geochemical Tools**. The National Science Foundation (NSF) provides funds for developing a new technique to fingerprint diagenetic fluids. 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 a tool to reveal the paragenesis of carbonates in particular dolomites. With a grant from NSF and matching support from the CSL and the Stable Isotope Laboratory a new mass spectometer was purchased which is capable of measuring the abundances of masses 47-49 in CO_2. These clumped isotope signatures are thought to be dependent only on temperature and thus temperature of formation of carbonate minerals can be detected. We will artificially produce carbonates at higher temperature in order to ascertain the temperature dependence of the $\Delta 47$ signal in these materials.

2010 Planned Projects

Carbonate Systems and Reservoir Characterization

- Capturing Carbonate Heterogeneity in Multiple Dimensions and Scales, Glover's Reef, Belize
- Assessing the Lateral and Stratigraphic Heterogeneity of a Windward Platform Margin, Exumas, Bahamas
- Characterizing Facies Heterogeneity in Pleistocene Marine and Eolian Deposits, New Providence Island, Bahamas
- Plio-Pleistocene Reef Development in the Southern Dominican Republic: Reef Growth and Facies Geometry during High-Frequency Sea-level Cycles
- Geospatial analyses and habitat characterization of cold-water coral mounds in the Straits of Florida (final year)
- Correlation of the Carbon Isotopic Composition of Organic Material Along a Platform-Basin Transect: Implications for the Use of Carbon Isotopes for Stratigraphic Purposes
- Connecting Outcrop to Subsurface: the Mixed Carbonate Siliciclastic System in the Neuquén Basin, Argentina (Year 2)
- Collation and Synthesis of Five Projects in the Mississippian Madison Formation

3D Visualization of Fractures, Karst and Fluid Flow

- Best Practice for Acquisition, Processing, and Interpretation of 3D GPR Data for Visualization of Deformation Bands, Fractures, and Karst in Carbonates
- Integration Of 3D GPR and Outcrop Analysis of Solution Enhanced Fractures and the 3D Visualization of Karst Cavities by GPR (Cassis, France)
- Time-lapse 3D GPR for Fluid Flow Quantification in Fractured Carbonates: Cretaceous Orfento Formation, Madonna della Mazza, Italy

Laboratory Experiments in Petrophysics

- Petrophysical Characterization of Plio-Pleistocene Reef Systems in the southern Dominican Republic
- The Importance of Early Cements in Maintaining Porosity and Permeability during Burial
- Electrical resistivity, Archie's Law and Pore Space Geometry in Carbonates

Exploration of New Geochemical Tools

- Clumped Isotopes: Application to Diagenesis
- Sulfur Isotopic Composition as a tool for Understanding Dolomitization: Application to Ancient Examples
- Testing Carbon Capture and Storage using Stable Isotope Measurements of CO2 in the Atmosphere

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 example, most of our deep-water coral work, and most of the funds for new equipment for the geochemical studies have been made possible by grants from federal funding agencies.

Reporting

The results of the projects will be presented at the **Annual Review meeting in Miami October 11-12, 2010**. In conjunction with the meeting a fieldtrip to the Belize barrier reef and the off-shore Glovers Reef is tentatively planned for **October 12-16, 2010.**

CARBONATE SYSTEMS AND RESERVOIR CHARACTERIZATION

Capturing Carbonate Heterogeneity in Multiple Dimensions and Scales, Glover's Reef, Belize

Noelle J. Van Ee, Gregor P. Eberli, Peter K. Swart and Donald F. McNeill

Project Purpose

Carbonate platforms are notoriously complex due to vertical and horizontal heterogeneity that makes the prediction of grain size, porosity, and sediment morphometrics difficult. Glover's Reef is a 260-km^2 reef-rimmed platform off the coast of Belize and the subject of both forward sediment and reservoir modeling studies (Figure 1). In the modern, the windward-leeward asymmetry and over 800 patch reefs in the lagoon introduce considerable heterogeneity in both facies and morphology. Rotary cores, over 100 km of seismic lines, satellite imagery, petrophysical measurements, and sediment samples from patch reefs and the marginal reef will allow rigorous quantitative assessment of carbonate heterogeneity in multiple dimensions and scales for the first time.

Key Deliverables

This project will provide a comprehensive, platform-wide dataset capturing carbonate heterogeneity on Glover's Reef from the late Quaternary until present. An integrated satellite facies, ground-truthed bathymetric, and sediment map, as well as geochemical, sedimentological, and petrophysical core data, will be made available to the Industrial Associates (Figures 1 and 2).

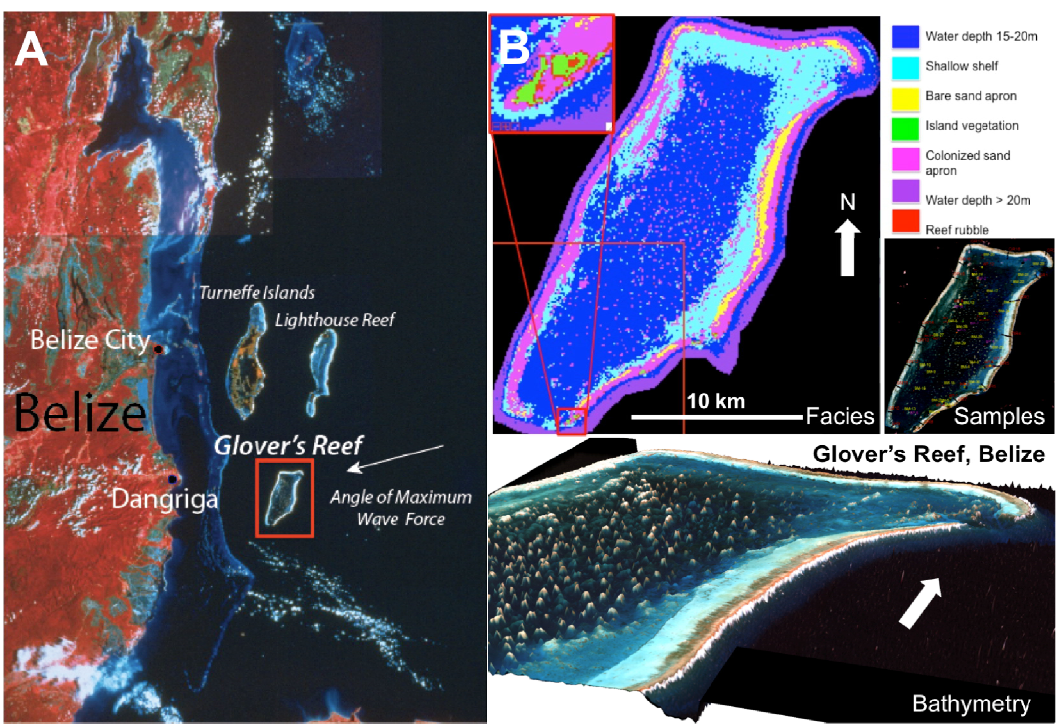

Figure 1. (A) Location of Glover's Reef. (B) Sediment grain size and component analysis, satellite imagery, and bathymetry will be incorporated into a map of modern facies.

Project Description

Classification of Landsat (30-m resolution) and IKONOS (4-m resolution) satellite imagery compared to ground-truthed bathymetry and sediment samples will be used to document facies heterogeneity on different scales. Landsat-based classification can image windward-leeward asymmetry on a platform scale, while high-resolution IKONOS imagery is needed to capture asymmetric morphology and facies changes on a patch reef scale (10s to 100s of meters).

Analyses of cores drilled through the reef margin, the patch reefs, and potentially the lagoonal setting will used to test the hypothesis that the vertical variability is dependent on location with respect to the platform. While cores taken from the rim record up to 9 meters of Holocene framestone and boundstone, Holocene sections of patch reef cores are comprised almost entirely of loose sand and coral rubble. The Pleistocene and Holocene patch reefs record ecological successions of biogenic grainstone and branching corals followed by *Montastraea annularis* coral framestones and finally coral rubble that are bounded by isotopically defined exposure horizons. While the entire patch reef sequence indicates vertical stacking within the lagoon, progradation appears to occur on the windward margin. Additionally, petrographic and petrophysical analysis will attempt to find relationships between depth, diagenetic overprint, porosity, permeability, and rock acoustic velocity. Acoustic velocities, in turn, will be used to improve the seismic velocity model for Glover's Reef lagoon. Finally, age control for the Pleistocene will be sought using U-Th and Sr-isotope dating techniques.

Expected Results

We expect to find that horizontal heterogeneity can be predicted in reference to the direction of dominant wind and wave energy and that this influence can be seen on the scales of both thousands and hundreds of meters. Vertical heterogeneity will follow predictable patterns that differ between lagoonal and margin settings and are governed by sea-level oscillations. Antecedent topography will be a major determinant of heterogeneity in both the vertical and horizontal directions. A specific mechanism for this control in reef environments will be suggested.

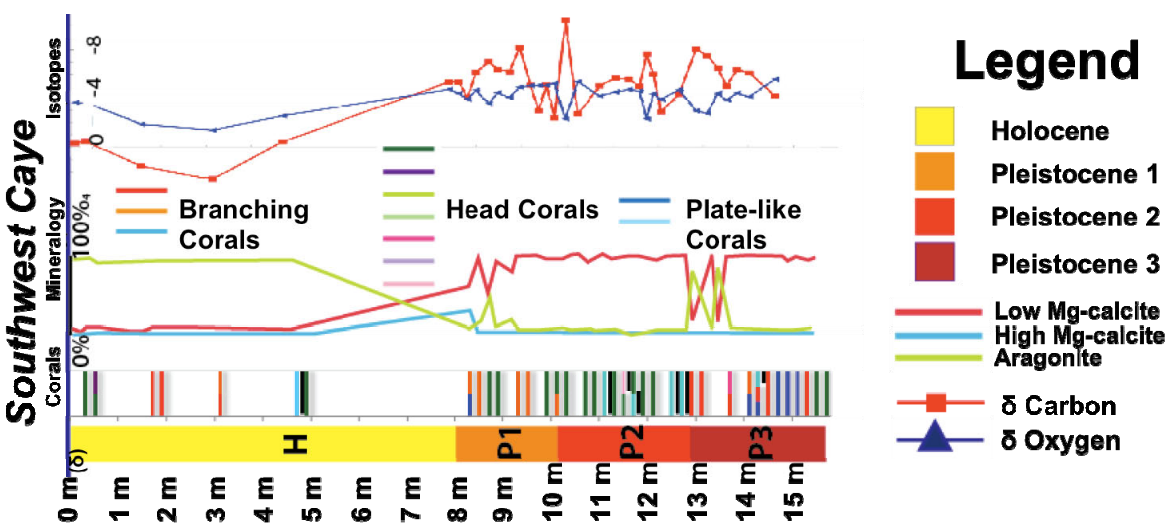

Figure 2. Southwest Caye core shown with coral, mineralogy, and isotope data.

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

Kelly L. Jackson, Angela Pumputis, Gregor P. Eberli, Donald F. McNeill, and Harold Hudson

Project Purpose

Windward margin stratigraphy and heterogeneity is assessed through mapping the modern facies and coring the Pleistocene parasequence-scale stratigraphy along the ~200 km windward margin in the Exumas, Bahamas (Fig. 1). The results from this three-year study will deliver a baseline for improved carbonate heterogeneity estimation and reservoir characterization in windward margin settings.

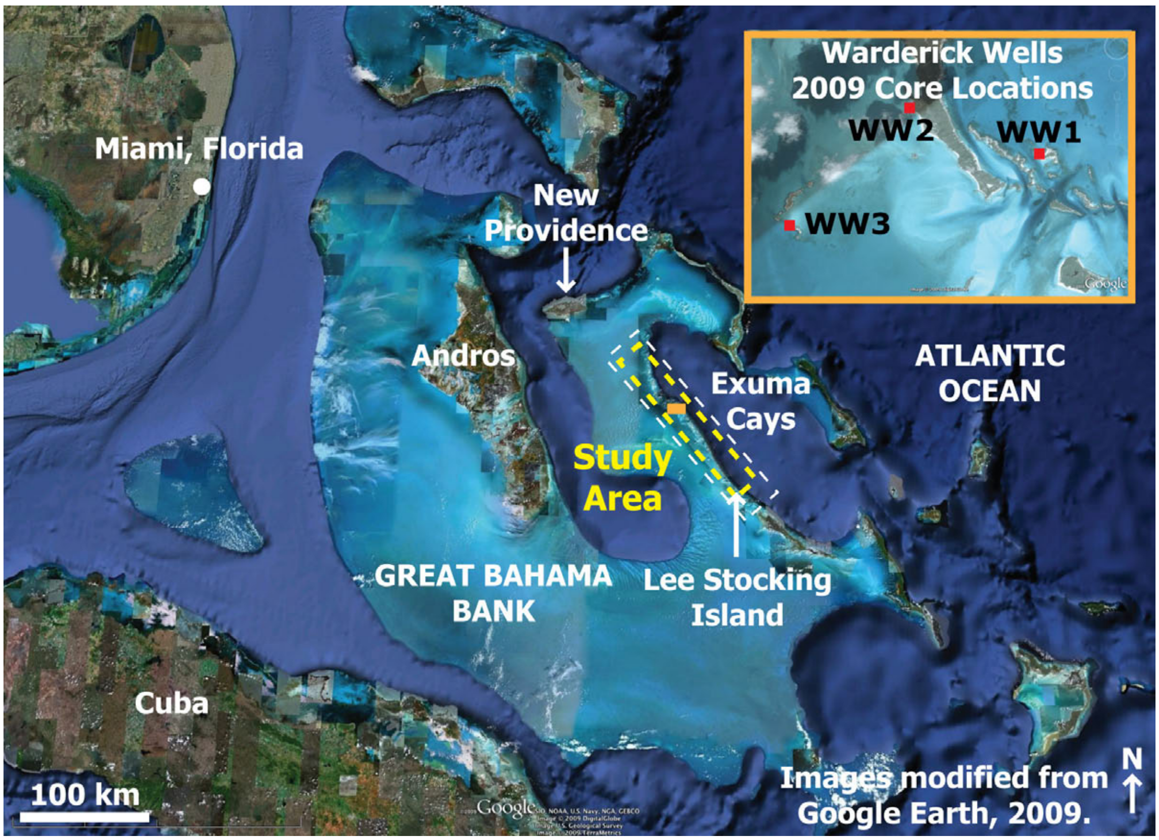

Figure 1. The Exuma Cays are located along the windward margin of Great Bahama Bank forming the western margin of Exuma Sound.

Project Background and Motivation

Sea level has changed throughout Earth's history with variable frequency and amplitude. In the Pleistocene, these changes occur quickly with high amplitudes due to the waxing and waning of ice sheets. During times of high sea level, carbonate platforms like the modern Great Bahama Bank are flooded and a new layer of sediment is deposited. Sea level, however, did not rise to the same level and was not always stable during the highstands. For example, during the last sea level highstand 125 kyrs ago during marine isotope stage (MIS) 5e, sea level peaked approximately 6 m higher than present and before that fluctuated for several meters (Thompson and Goldstein, 2005). Likewise, older sea level highstands were also higher (MIS 9 and 11) or lower (MIS 7) than the current sea level. The Quaternary stratigraphy of the Bahamas records the depositional events occurring during highstands in a complicated array of stacked and laterally accreting marine and eolian deposits for example on Eleuthera Island (Kindler and Hearty, 1996) and New Providence Island (Garret and Gould, 1984; Hearty and Kindler, 1997). Along the Exumas platform margin, the highstand variability and impacts of sea level changes are recorded in stacked successions of shallow-water carbonates (McNeill and Hearty, 2009; Petrie, 2010).

By dissecting the sedimentary architecture, we expect to address the fundamental question of how the frequency and amplitude of sea level influences the stratigraphic facies heterogeneity. Platform interior cycles created by high-frequency sea level changes often maintain uniform thicknesses over several kilometers and their vertical trends in thickness delineate larger scale reservoir units. In marginal settings, cycles vary greatly in shape and because the elevation of each sea level rise varies, a complicated architecture of onlapping and overstepping wedges is produced. 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 stack laterally and prograde seaward. In the Lee Stocking Island area, the Exumas margin prograded eastward from the older middle Pleistocene (potentially MIS 11 or 13) to the late Pleistocene (MIS 5) (McNeill and Hearty, 2009).

Project Hypothesis

The central hypothesis of this study is that the windward margin stratigraphic architecture records the high-frequency sea level fluctuations within Pleistocene sea level highstands.

Project Tasks

The hypothesis will be tested by mapping the modern facies and Pleistocene outcrops in addition to coring and dating the Pleistocene parasequences in the Exuma Cays, Bahamas (Fig. 1). Holocene facies mosaics will be evaluated with respect to the underlying Pleistocene topography. Dating of individual parasequences will relate vertical successions to the different Pleistocene sea level changes.

Task 1: Produce detailed geologic maps of the Exumas windward margin by combining satellite imagery and surface mapping of the Pleistocene/Holocene strata. Initial reconnaissance field mapping was conducted in 2009 and will continue with surface mapping of outcropping Pleistocene units. This mapping will be integrated with previous studies by McNeill and Hearty (2009) and Petrie (2010) to produce a detailed surface geologic map of the Exumas windward margin. Detailed surface mapping is scheduled for the areas between Warderick Wells and Lee Stocking Island.

Task 2: Collect core transects to establish the vertical succession and stacking patterns at key locations. Cores, up to 10 m deep, will be collected using a rotary drill with a tripod and wire-line core barrel system (Fig. 2A). Short 1 m cores will be collected using handheld system (Fig. 2B). Rocks in cores collected at Warderick Wells (Fig. 1A inset) feature a grainstone texture but the sedimentary structures indicate deposition in tidal, beach, and eolian environments. Up to three successions, separated by exposure horizons, document deposition during three Pleistocene sea level highstands. The successions are tentatively correlated to the sea level highstands occurring during MIS 5, 9, and 11 (120, 320, and 400 kybp, respectively). Future dating is planned to confirm these estimates (see Task 3). Transects of cores will test the idea that the Exumas prograded eastward from the older middle Pleistocene (MIS 11 or 13) to the late Pleistocene (MIS 5) as hypothesized by McNeill and Hearty (2009). A ten day drilling campaign is planned for September 2010 onboard the R/V Coral Reef II to recover additional long cores at various locations along the Exumas windward margin. Small cores will be collected during this drilling cruise as well as during other field campaigns in the spring and summer of 2010.

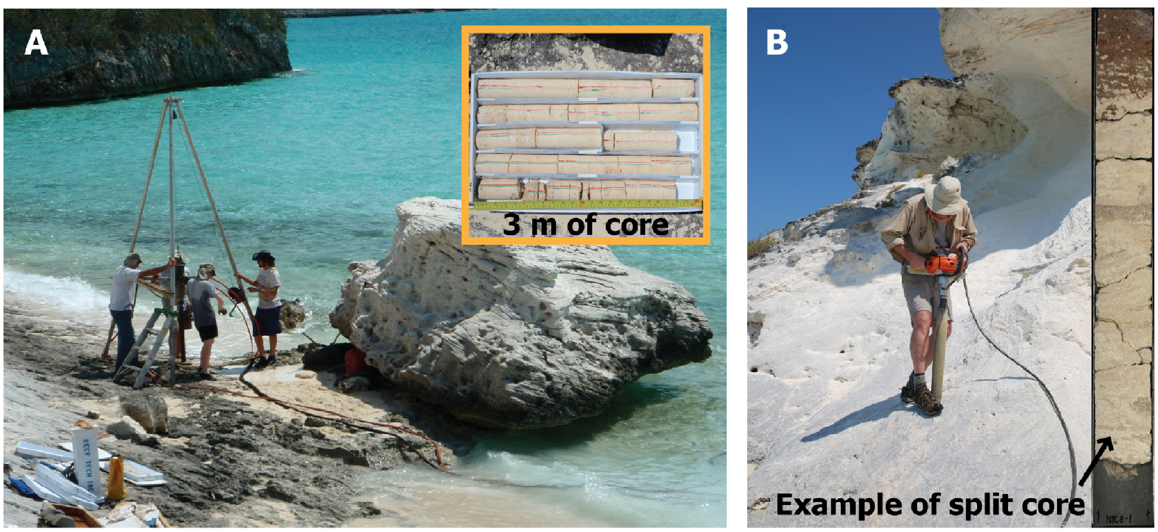

Figure 2. Drilling methods. (A) A rotary drill with a tripod and wire-line core barrel system was used to collect 5 long cores in April 2009. This setup will be used during the summer 2010 coring campaign. (B) Numerous short cores will be collected during the summer of 2010 using a hand-held coring device to create high-density Pleistocene core transects throughout many islands in the Exuma Cays.

Task 3: Age dating of Pleistocene and Holocene strata to correlate and decipher the amplitudes of Pleistocene sea level changes. To date the Pleistocene facies, we will use a combination of U-Th dating and amino acid racemization.

Task 4: Conduct petrophysical analyses to understand the pore scale rock-fluid interactions of a carbonate windward margin. Petrophysical analyses conducted on the NER Autolab 1000 will measure porosity, permeability, Vp, under variable confining pressure, and the pore fluid pressure of carbonate facies. These results will provide the rock type characterization of carbonate platform margin reservoir analogs.

Expected Results

This study will document the lateral and vertical heterogeneity of the grain-dominated windward margin produced by the sedimentary response to high-frequency sea level changes. The expected outcome is to decipher the ages of orbitally induced sea level changes, the small-scale, high frequency variations during the highstands, and document stratigraphic heterogeneity in relation to the Pleistocene sea level fluctuations. Core data will decipher the coastal response to sea level fluctuations on a windward carbonate platform margin to determine the impact on coastal systems and resulting facies heterogeneity. This interaction directly influences biodiversity including the distributions of stromatolite and coral reef communities (Fairbanks, 1989; Feldmann and McKenzie, 1998). Assessing the stratigraphic heterogeneity of a carbonate platform margin will directly impact hydrocarbon reservoir characterization from the rock pore to the platform margin scale in coastal carbonate systems.

References

Fairbanks, R. G., 1989, A 17,000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation: Nature, v. 342, p. 637-642.

Feldmann, M., and McKenzie, J. A., Stromatolite-thrombolite associations in a modern environment, Lee Stocking Island, Bahamas, Palaios, v. 13, p. 201-212, 1998.

Garrett, P., and Gould, S.J., 1984. Geology of New Providence Island, Bahamas: Geological Society of America Bulletin, v. 95, p. 209-220.

Hearty, P.J., and Kindler, P., 1997, The stratigraphy and surficial geology of New Providence and surrounding islands, Bahamas: Journal of Coastal Research, v. 13, n. 3, p. 798-812.

Kindler, P. and Hearty, P.J., 1996, Carbonate petrography as an indicator of climate and sea-level changes: new data from Bahamian Quaternary units. Sedimentology v. 43, p. 381-399.

McNeill, D. F., and Hearty, P., 2009, Windward carbonate margin parasequence geometry linked to precursor topography, Exuma Cays, Bahamas: American Association of Petroleum Geologists Annual Meeting, Denver, CO, Abstract.

Petrie, M., 2010, Sedimentology of a Grain-dominated Tidal Flat, Tidal Delta, and Eolianite System: Shroud Cay, Exumas, Bahamas, M.S. Thesis, University of Miami, 277 pp., unpublished.

Thompson, W. G., and Goldstein, S. L., Open-system coral ages reveal persistent suborbital sea-level cycles, Science, v. 308, p. 401-404, 2005.

Characterizing Facies Heterogeneity in Pleistocene Marine and Eolian Deposits, New Providence Island, Bahamas

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

Background and Purpose

New Providence Island is formed by vertical and lateral successions of subtidal, beach, and eolian deposits during several Pleistocene sea level highstands (Garrett and Gould, 1984; Hearty and Kindler, 1997). As a result, the ~200 km^2 island is a complex patchwork of facies of different ages but discrepancies remain concerning the timing of deposits in relation to Pleistocene sea level highstands. For example, Hearty and Kindler (1997) proposed that during MIS 7, eolianites built to higher relief than those during MIS 5e. But, sea level during MIS 7 was ~-17 m while it was ~+5 m during MIS 5e (Haddad et al., 1993). In addition, there is documentation that the last highstand MIS 5e experienced fluctuations of the sea level in the order of 10 – 15 m. Similar fluctuations can be expected within older highstands. New Providence Island potentially has the record of these fluctuations in the laterally accreted eolian and beach ridges. This aim of this project is to relate the island stratigraphy to the Pleistocene highstands and the fluctuations within the highstands while at the same time document and explain the facies heterogeneity and the accretionary history of New Providence Island.

Scope of Work

This project will refine the documentation of the complex facies heterogeneity of juxtaposed ages, environments, and compositions on New Providence Island using the working hypothesis that the island formed through vertical and lateral accretion of marine and eolian deposits during the last three Pleistocene sea-level highstands (MIS 5, 9, and 11). Detailed stratigraphy both in outcrop and subsurface will be used to map out deposits across the island. This mapping, combined with detailed petrography of all units, will create a depositional and

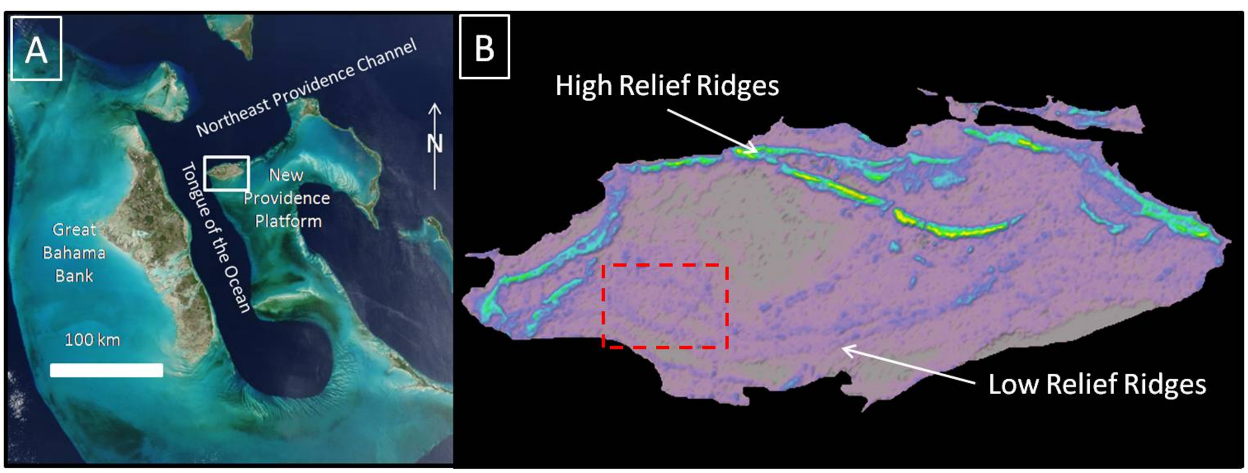

Figure 1. (A) Map of the Bahamas; white square shows the position of New Providence Island. (B) False color image of elevation across New Providence Island; red box indicates location of proposed GPS survey.

diagenetic history of New Providence Island. Radiometric dating techniques will give the precise timing of deposition that is needed to relate the deposits to Pleistocene sea level changes. The beach facies within each one of the stratigraphic packages will provide an anchor point for the amplitude of sea level in each of the highstands.

Project Description

In a first phase of fieldwork, facies and ages were mapped (Fig. 2). These maps show the lateral relationships of environments of deposition across New Providence Island, documenting facies heterogeneity with juxtaposed ages, compositions, and environments across a relatively small area. This year's fieldwork will focus on the detailed description of key outcrops. The Serenity Outcrop on the northwest side of New Providence Island shows prograding back-beach dune ridge systems, likely from MIS 5e. Bedding geometries of this outcrop will be mapped at high resolution to illustrate the internal facies architecture of such ridges. In addition, beach ridges to the south that show a punctuated sea level fall probably at the end of MIS 5e will be surveyed precisely using GPS measurements to assess the magnitude of each sea-level drop and thus the ice buildup associated with each subsequent ridge. Discontinuities in the eolian dunes at Collins Avenue, Travellers Rest, and the Queen's Staircase in northern New Providence will be carefully examined for paleosol development, as they may be evidence for sub-orbital-scale sea level fluctuations within MIS 5e suggested by Thompson and Goldstein (2005).

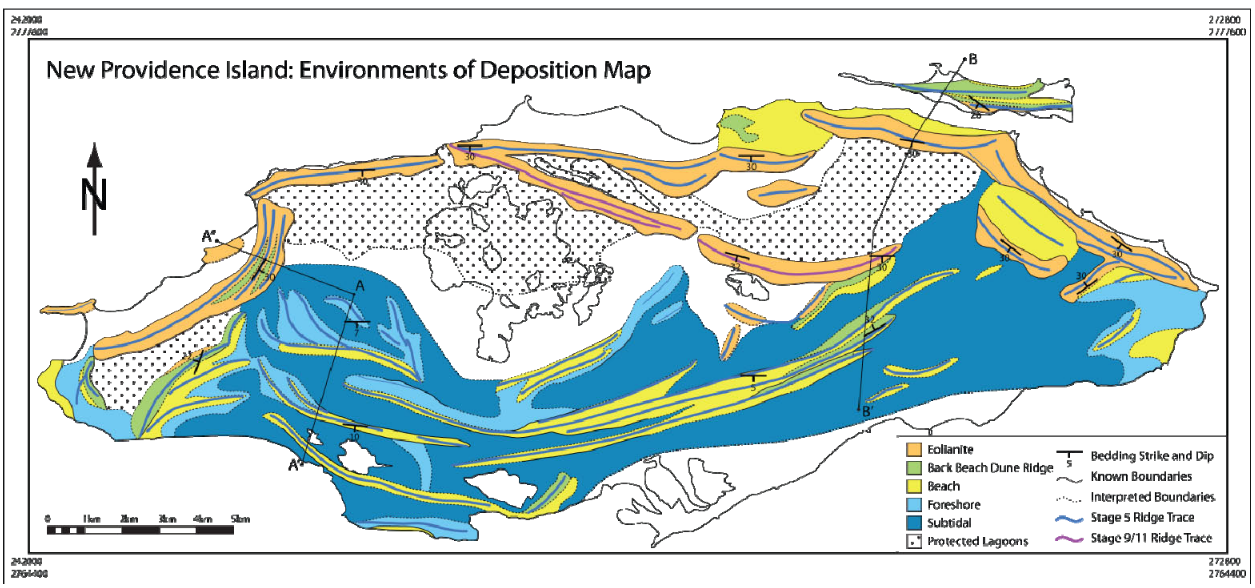

Figure 2. Map of environments of deposition across New Providence Island based on phase one of fieldwork.

Dating of the different ridges will be crucial for unraveling the sequence of depositional events on New Providence Island. Fossil shell samples have been collected from multiple locations across New Providence for U/Th dating. Initial tests show that the shells of land snail *Cerion sp.* can also contain enough Uranium for U/Th dating. Additionally, another dating method that may be employed involves plotting the $^{87}Sr/^{86}Sr$ ratios from marine fossils on the

LOWESS fit for the marine Sr-isotope record in order to get numerical ages (McArthur et al., 2001).

In addition to the description of geometry and sedimentary structure within each ridge, thin section analysis is performed to document the composition and diagenetic histories of the different facies (Fig. 3). Of particular interest is the variable meteoric overprint of the different Pleistocene ridges. A cement stratigraphy is attempted and compared to the ages and relative succession of the ridges. Additionally, porosity and pore types will be classified to better understand the reservoir potential of these facies.

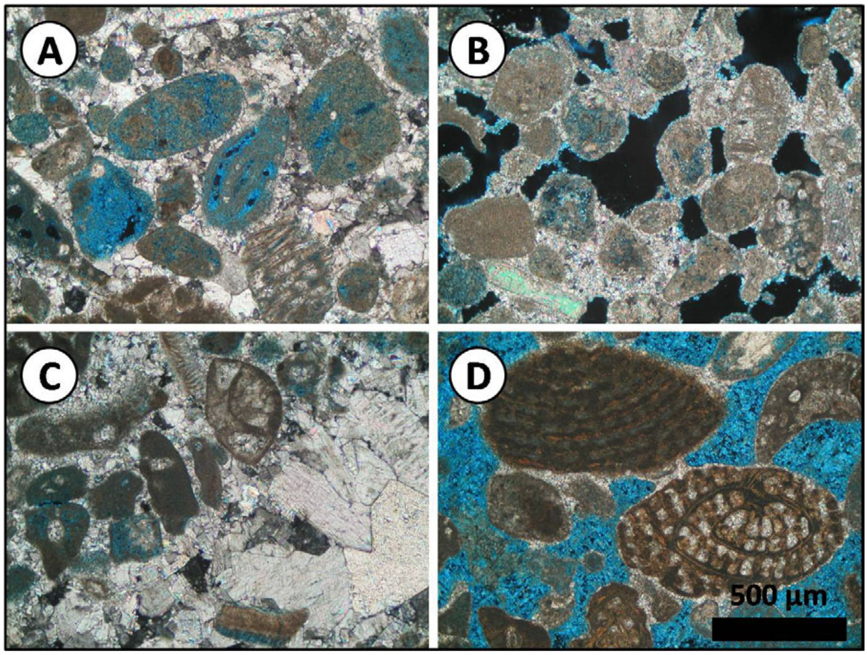

Figure 3. Thin section photomicrographs displaying variations in composition and cementation. (A) Skeletal peloidal grainstone with partly dissolved grains. (B) Grainstone with early marine cement and interpartical and microporosity (in the grains). (C) Skeletal grainstone with abundant blocky spar. (D) Skeletal grainstone with meniscus cement.

In addition to >20 short cores (<1 m) from New Providence Island, two sets of long cores are available for interpretation. Multiple ~30 m cores from Clifton Pier (Aurell et al., 1997) are available to the University of Miami for correlation with outcrop stratigraphy. In addition, four cores up to ~20 m are available from the western end of Arawak Key near Nassau Harbor which will require retrieval from the Bahamas for study at the University of Miami. These two sets of cores will be used to create a 3D model of facies heterogeneity across New Providence Island.

Deliverables

- Traditional outcrop mapping, core descriptions, and petrographic analyses will provide a comprehensive documentation of facies heterogeneity in 3D across New Providence Island.
- Detailed sedimentologic and petrographic description of the laterally accreting dune ridges.
- Documentation of the juxtaposition of facies of different ages based on the radiometric dates within the Pleistocene.
- Precise assessment of the down-stepping beach ridges to provide the magnitudes of the punctuated sea level fall leading into the last major glaciations.

Expected Results

The results of this project will provide much-needed information on the instability of sea level highstands and the resultant temporal and spatial facies heterogeneity within a grainstone facies. In addition, detailed documentation of each facies type will provide a useful bank of information that can be used to identify similar deposits in the subsurface.

References

Aurell, M., McNeill, D.F., Guyomard, T., Kindler, P., 1995. Pleistocene shallowing-upward sequences in New Providence, Bahamas: signature of high-frequency sea-level fluctuations in shallow carbonate platforms: Journal of Sedimentary Research, v. B65, p. 170-182.

Garrett, P., and Gould, S.J., 1984. Geology of New Providence Island, Bahamas: Geological Society of America Bulletin, v. 95, p. 209-220.

Haddad, G.A., Droxler, A.W., Kroon, D., and Müller, D.W., 1993. Quaternary $CaCO_3$ input and preservation within Antarctic intermediate water: mineralogic and isotopic results from holes 818B and 817A, Townsville Trough (Northeastern Australia margin): Proceedings of the Ocean Drilling Program, Scientific results, v. 133, p. 203-233.

Hearty, P.J., and Kindler, P., 1997. The stratigraphy and surficial geology of New Providence and surrounding islands, Bahamas: Journal of Coastal Research, v. 13, n. 3, p. 798-812.

McArthur, J.M., Howarth, R.J., and Bailey, T.R., 2001. Strontium isotope stratigraphy: LOWESS Version 3: best fir to marine Sr-isotope curve for 0-509 Ma and accompanying look-up table for deriving numerical age: The Journal of Geology, v. 109, p. 155-170.

Thompson, W.G. and Goldstein, S.L. 2005, Open system coral ages reveal persistent suborbital sea-level cycles: Science, v. 308, p. 401-404.

Plio-Pleistocene Reef Development in the Southern Dominican Republic: Reef Growth and Facies Geometry during High-Frequency Sea-level Cycles

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

Project Purpose

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. This project aims to characterize the composition, morphology and distribution of fringing reefs developed along the southern coast of the Dominican Republic. This study will be conducted in conjunction with the petrophysical characterization included in this Prospectus.

Key Deliverables

This project will provide some of the first seismic data of fringing reef development during an extended period of high-frequency sea-level change. By integrating this data with both core and outcrop investigations we will provide an integrated model of reef growth and facies geometries during the Plio-Pleistocene. Results will be presented at the Annual Review and images and data made available to the Industrial Associates.

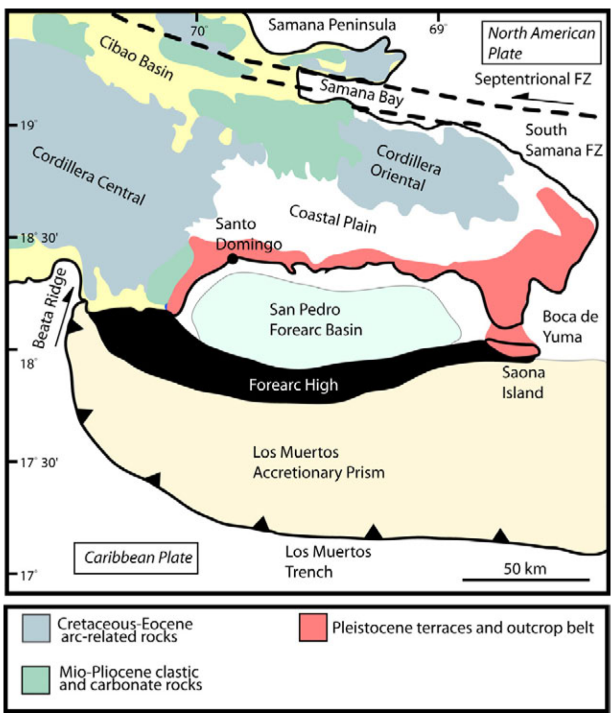

Figure 1. Geologic and tectonic map of southeastern Dominican Republic. The Pleistocene terrace and outcrop belt is shown in red. Modified from Mann et al. (1995).

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 1). Six to eight fairly continuous terraces are encountered in a belt of coastal reef limestones. An integrated coring, outcrop, and seismic study of the fringing reef deposits on the southern coast of the Dominican Republic has been initiated to determine the morphology and facies geometries of fringing reefs during high-frequency sea-level cycles. Seismic data in the area east of Santo Domingo (Figure 2), acquired by Petroleras las Mercedes in the late 1970’s, and some lines are available through the Direccion General de Minera of the Dominican Republic and will be scanned and digitized. This seismic data, in conjunction numerous shallow outcrops and a core transect perpendicular to the southern coast, will allow us to determine stratigraphic relationships of different reef building events, subsurface facies distributions, and overall reef geometries. Seismic profiles will also be integrated with offshore seismic lines from the San Pedro Basin.

Project Description

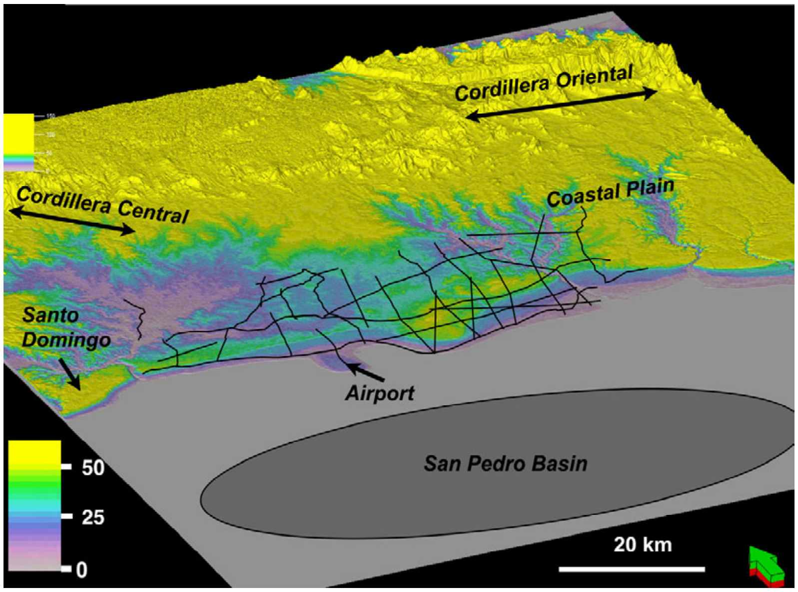

Figure 2. Digital elevation model of the southern coast of Dominican Republic east of the capital city Santo Domingo. The limestone terraces in this area are being extensively quarried which provides numerous outcrop exposures to different reef building events. Black lines indicate the position of seismic lines acquired by Petroleras Las Mercedes.

For the past two years we have been investigating the composition and stratigraphic relationships of the highstand reef deposits on the southern coast of the Dominican Republic. Like Barbados and the coast of Huon Peninsula, New Guinea, the reef terraces are preserved by long-term tectonic uplift, such that the youngest formations are located at the lowest elevations close to the present coast, and older reef terraces at higher elevations and further inland. Based on our early outcrop studies we have developed a preliminary model of the ages and stratigraphic relationships of the reef terraces (Figure 3). This model is based on confirmed radiometric ages of the youngest (6 m) terraces that date to ~125 Ka, estimated rates of tectonic uplift (Mann et al., 1995), and changes in the reef faunal composition. Reefs of the younger terraces are dominated by modern reef coral *Acropora palmata*. Reefs of the higher terraces and subsurface quarry exposures are often dominated by the extinct reef coral *Stylophora*. One aspect of this study will be to confirm this proposed age model through strontium isotope, radiometric, and paleomagnetic age dating.

Seismic analyses and coring studies will allow us to further refine the stratigraphic relationships and geometries of each of the highstand reef building events. Furthermore, these studies will allow us to integrate the surface geology into a broader temporal and geographic context. The seismic profiles will allow us to examine changes in fringing reef morphology underlying the surface terraces and determine how fringing reef development was influenced by Pleistocene climatic fluctuations and dramatic changes in the reef building fauna (Huebeck et al., 1991). We will also correlate the onshore seismic data with offshore data collected in the San Pedro Basin (Ladd et al., 1981). This should provide a complete onshore-offshore record of deposition during the Plio-Pleistocene climatic transition (Figure 3).

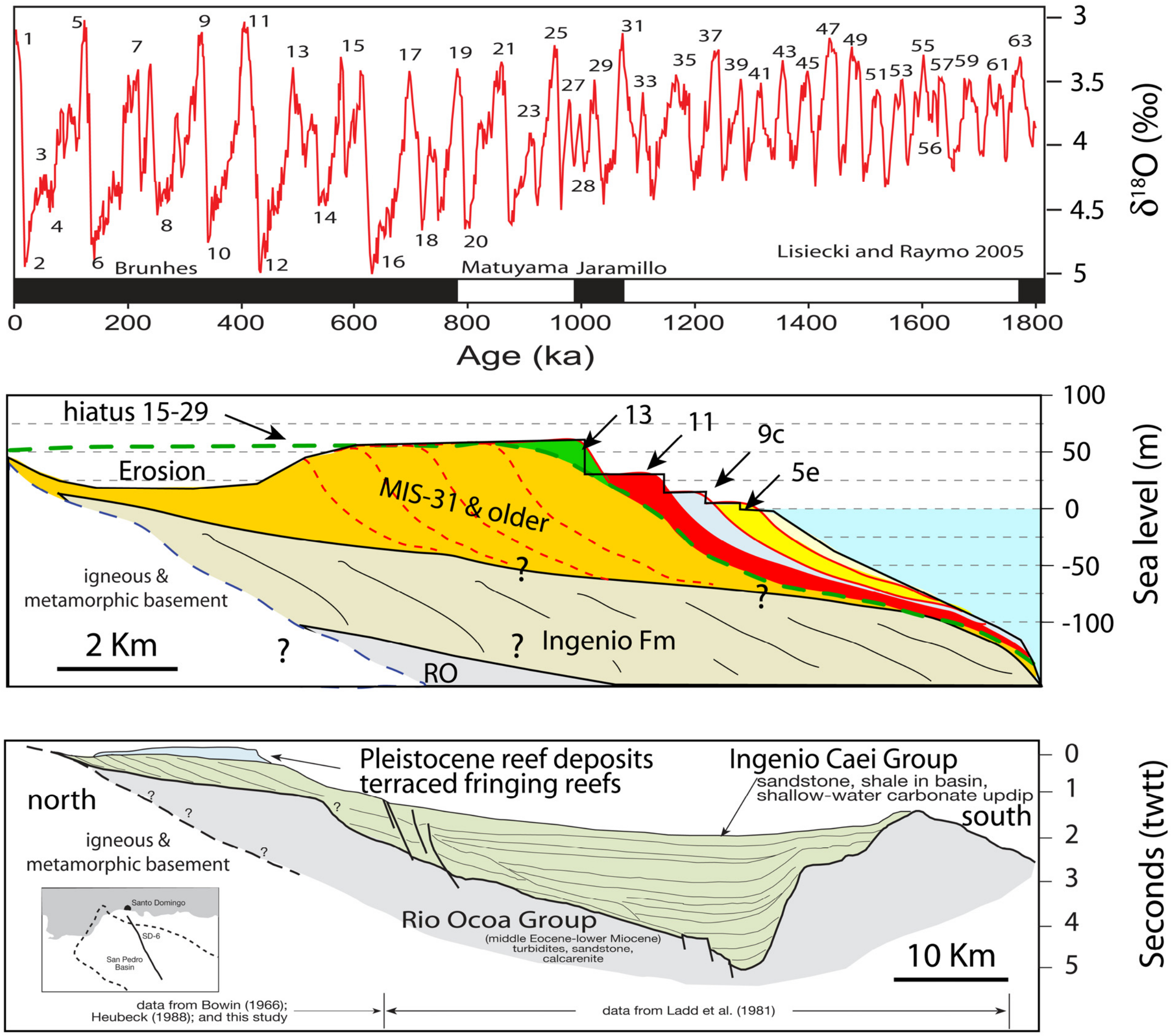

Figure 3. (Top) Pleistocene oxygen isotope record showing the timing and intensity of high-frequency sea level events. (middle) Cross-sectional model of Plio-Pleistocene reef development on the southern coast of the Dominican Republic. Reef building events are labeled according to the marine isotope stages above. (Bottom) Cross-sectional model showing the relationship of the Pleistocene reef terraces and both the onshore and offshore Ingenio Caei Group.

References

Huebeck, C., P. Mann, J. Dolan, and S. Monechi, 1991, Diachronous uplift and recycling of sedimentary basins during Cenozoic tectonic transpression, northeastern Caribbean plate margin: Sedimentary Geology, vol. 70, p. 1-32.

Ladd, J., T. C. Shih, and C. J. Tsai, 1981, Cenozoic tectonics of Central Hispaniolsa and adjacent Caribbean Sea: AAPG Bulletin, vol. 65, p. 466-489.

Mann, P., F. W. Taylor, R. Lawrence Edwards, and T. Ku, 1995, Actively evolving microplate formation by oblique collision and sideways motion along strike-slip faults: An example from the northeastern Caribbean plate margin, Tectonophysics, vol. 246, p. 1-69.

Geospatial analyses and habitat characterization of cold-water coral mounds in the Straits of Florida (*final year*)

Thiago B.S. Correa, Klaas Verwer, Gregor P. Eberli, Mark Grasmueck, and Sam Purkis

[1]*Nova Southeastern University, Dania Beach, FL*

Project rationale

High-resolution satellite imageries have been used to quantify the facies patterns of modern carbonate depositional environments (Harris & Kowalik, 1994). Geobodies (e.g., reefs, shoals) are extracted from these images and then analyzed statistically using a suite of geospatial metrics. Data on the size, shape, and frequency-area relationships of geobodies can be used to refine geological models and to assist with interpretations of the subsurface (Rankey, 2002; Purkis et al., 2005). Remotely sensed optical tools, however, cannot penetrate to deep-water environments and therefore, morphometric-based spatial analyses have been restricted to the shallow-water realm. Thus, deep-water reefal depositional environments represent a new frontier in geospatial analyses.

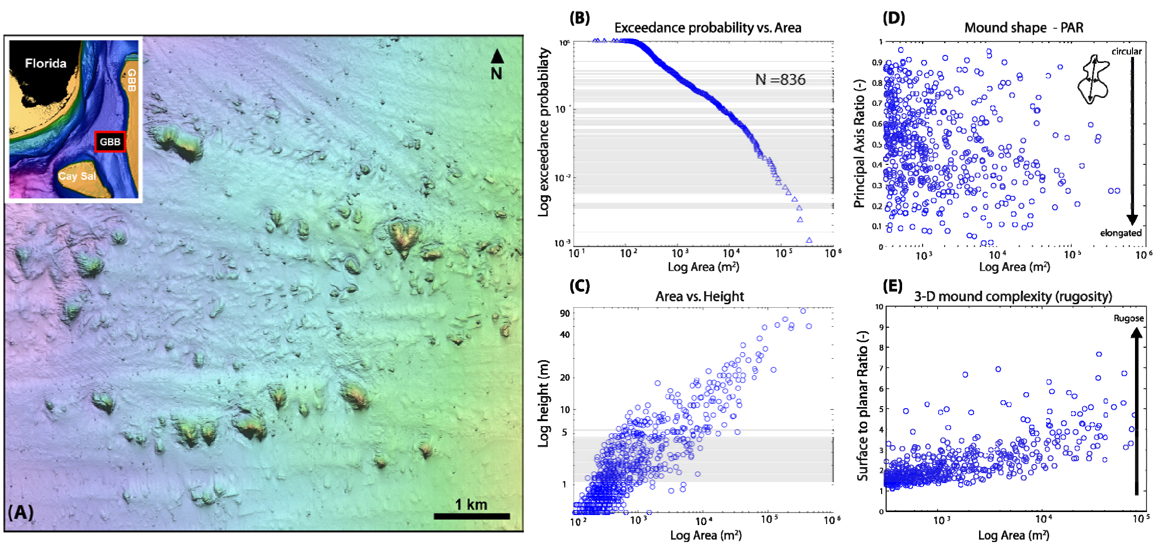

Figure 1. (A) Topographic map of GBB site depicting isolated, individual mounds. Inset, upper left, shows the location of GBB site in the Straits of Florida. (B-E) Graphs report morphometrics for GBB mounds.

Scope of work

Autonomous Underwater Vehicle (AUV) surveys were conducted on cold-water coral mounds in the Straits of Florida from 590 to 860 m water depths. The AUV was equipped with multibeam and side-scan sonar systems that produced a digital elevation model (DEM) and acoustic seabed maps of the seafloor at up to 0.5 m-resolution. Combined with submersible ground-truthing, this unique dataset will allow us to quantify the spatial distribution of coral mounds as well as their facies distribution(s). The AUV also simultaneously collected sub-surface and current regime data over large areas (i.e., tens of km^2). The integrated nature of this combined dataset will undoubtedly provide insights regarding the influence of hydrodynamics and antecedent topography on facies heterogeneity in deep-water environments the Straits of Florida.

Preliminary Results

In 2009 we presented the first results of morphometric analyses for two distinctive sites in the Straits of Florida. For the site characterized by several individual buildups at the slope of Great Bahama Bank (Figure 1), mound perimeter was automatically extracted from the DEM (based on a cutoff of 8°). Subsequently, each mound was statistically analyzed in terms of shape, size-frequency distribution, and complexity (Figure 1). For the site at the base of the Miami Terrace, habitat facies were discriminated from the side-scan sonar and then analyzed in terms of bathymetric variables (e.g., azimuth) using the DEM. Together, analyses for the two sites showed that intrinsic (e.g., antecedent topography) and extrinsic (e.g., current) factors control mound morphology in the Straits of Florida. This coming year, we will complete our analyses for the remaining three sites. These results will broaden our understanding of the forces that control mound distribution, geometry, and development.

Project Objectives

This work aims to: (1) quantitatively discriminate and extract the habitat facies of three cold-water coral field in the Straits of Florida using an integrated dataset; (2) correlate the resulting habitat maps with local topography using spatial statistical analysis; and (3) correlate the observed mound spatial distributions with local current regime in order to gain insights into facies pattern(s) within deep-water carbonate environments.

Key Deliverables

This project will generate high-resolution habitat characterization maps for all surveyed cold-water coral sites in the Straits of Florida. The lateral variability of each habitat facies will be determined. Morphometric parameters will be calculated for each site and statistically correlated with environmental factors, including current regime and antecedent topography.

References

Harris PM, Kowalik WS (1994) Satellite images of carbonate depositional setting: examples of reservoir and exploration scale geologic facies variation, Vol, Tulsa, OK.

Purkis SJ, Riegl BM, Andrefouet S (2005) Remote Sensing of Geomorphology and Facies Patterns on a modern carbonate Ramp (Arabian Gulf, Dubai, U.A.E). Journal of Sedimentary Research 75: 861-876.

Rankey EC (2002) Spatial patterns of sediment accumulation on a Holocene carbonate tidal flat, northwest Andros Island, Bahamas. Journal of Sedimentary Research 72: 591-601.

Correlation of the Carbon Isotopic Composition of Organic Material Along a Platform-Basin Transect: Implications for the Use of Carbon Isotopes for Stratigraphic Purposes

Amanda Oehlert and Peter K. Swart

Project Purpose

The carbon isotopic composition of periplatform sediments deposited over the past 10 million years on the Great Bahama Bank (GBB) does not agree with the $\delta^{13}C$ record of pelagic sediments used in global reconstructions. A remote possibility exists that the $\delta^{13}C$ of the periplatform sediments may have been affected by diagenesis; therefore, we have examined the $\delta^{13}C$ of the organic material. A positive correlation between the $\delta^{13}C$ of the organic and inorganic fractions would preclude the possibility of diagenetic alteration. Currently, four cores recovered from ODP Leg 166 have been used to characterize the relationship between the inorganic and organic fractions in periplatform sediments (Figure 1). Both fractions have been analyzed in each core to a

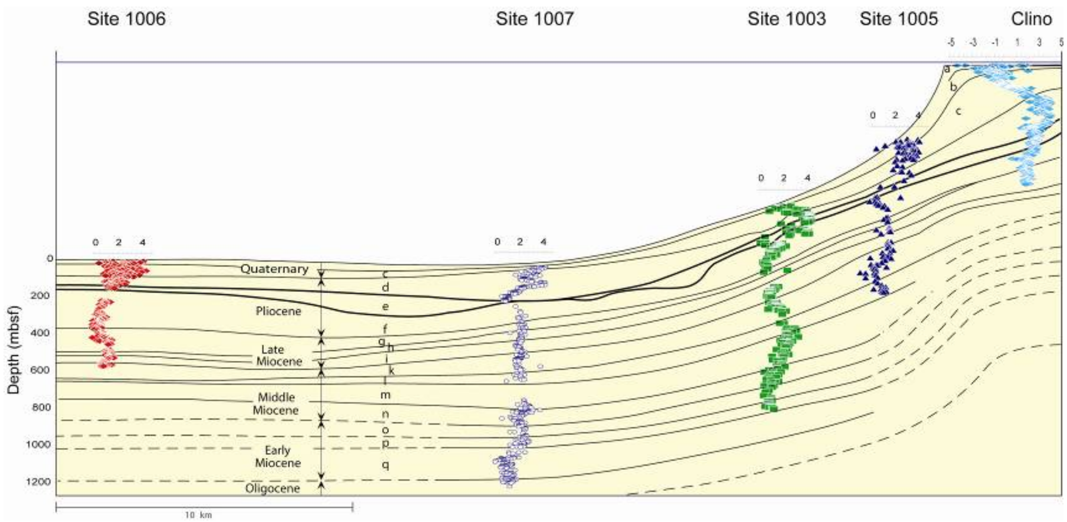

Figure 1. Profile of GBB, showing location of cores analyzed with inorganic carbon records overlaying seismic sequences.

depth of 150 meters below sea floor (mbsf). This current phase of the project aims to extend the records of $\delta^{13}C$ of the organic material to the bottom of each of the four cores, allowing the characterization of both carbon isotopic records at GBB from the late Oligocene to the recent past. High-resolution sampling and analysis of cores 1003, 1005, 1006, and 1007 will be used to evaluate spatial variations in the carbon isotopic records, as well as to assess the validity of calculating pCO_2 from the difference between organic and inorganic carbon fractions.

Scope of Work

The transect of cores recovered off the margin of Great Bahama Bank during Leg 166 all exhibit the same pattern in inorganic carbon composition over the past 10 myr (Swart, 2008; Swart and Eberli, 2005). It was suggested that the consistent patterns identified between the various sites relates to the relationship between platform productivity and sea level cycles. During sea level highstands, the carbonate factory is in full production mode, and exports coarse-grained, platform carbonate material to the slope. In contrast, platform exposure during sea level lowstands shuts off the carbonate factory, resulting in low stand deposition of primarily pelagic sediments. Supporting evidence for this hypothesis is provided by the analysis of the $\delta^{13}C$ of organic material. The $\delta^{13}C$ of organic material from the sediments produced on the platform surface is significantly more positive than the pelagic organic material, therefore patterns of highstand productivity should be identifiable in the organic carbon record.

During the next phase of the project, we will extend the records of inorganic and organic carbon isotopes of sediments recovered along the entire Bahamas Transect on the leeward side of Great Bahama Bank during ODP Leg 166. The extended records from the cores at ODP Sites 1003-1007 will be used to identify whether or not this pattern has been consistent throughout geologic time. The isotopic data will be related to sedimentary units associated with the sequence boundaries identified in the Initial Report of ODP Leg 166.

Key Deliverables

The results of this project will provide new insights into (i) the correlation between the inorganic and organic carbon fractions measured in the basin sediments, and its subsequent degradation in the middle and upper slope cores, (ii) the utility of using stable carbon isotopes for stratigraphic correlation, and (iii) the use of the difference in the $\delta^{13}C$ between organic and inorganic components as indicators of the pCO_2 in the atmosphere.

Project Description

The $\delta^{13}C$ of organic and inorganic components will be measured on sediments collected from cores drilled during the ODP Leg 166. Initial data demonstrate a strongly positive correlation (r^2=0.512) between organic and inorganic fractions in the basin sediments collected from ODP Site 1006. This relationship breaks down at the toe-of-slope of Great Bahama Bank (Site 1007), and continues to disintegrate

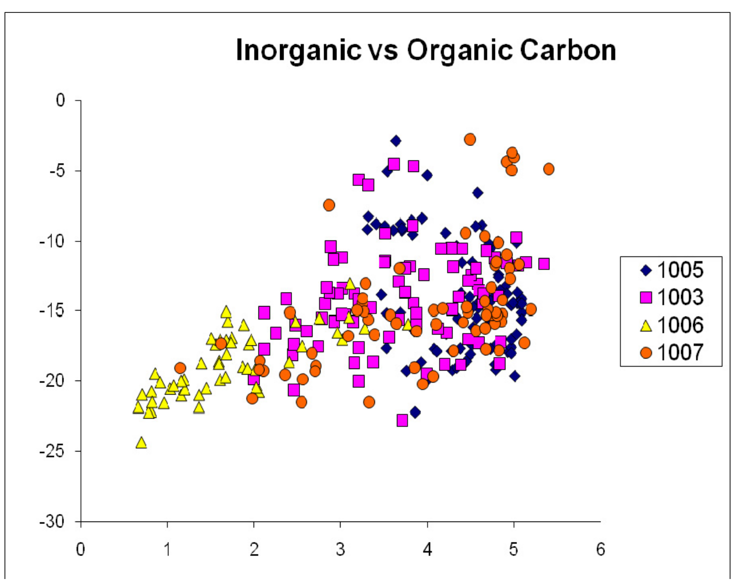

Figure 2. Plot of inorganic vs. organic carbon isotopes.

until the upper slope (Site 1005), where this relationship shows the potential to reverse (Figure 2). The next phase of this project will extend the depths of the organic carbon isotopic record in order to clarify these relationships, and will consider the effects of spatial changes in source variability during platform development.

The records generated by this study will result in a ~20 myr record of carbon isotopic composition of an active shallow marine carbonate platform. Therefore, a unique dataset highlighting the relationship between inorganic and organic carbon fractions in periplatform sediments will be assembled. Furthermore, the application of carbon isotopes in creating stratigraphic correlations and their utility in the estimation of pCO_2 will also be evaluated. The results of these analyses will provide a modern analog to uplifted shallow marine carbonate platforms with similar development histories such as the Maiella platform in Italy (Eberli et al., 2004) .

References

Eberli, G. P. Anselmetti, F.S., Betzler, C. Van Konijnenburg, J.-H., and Bernoulli, D., 2004, Carbonate platform to basin transition on seismic data and in outcrop – Great Bahama Bank and the Maiella platform, Italy. In Eberli, G.P., Massaferro, J.L., Sarg, J.F. (eds.) Seismic Imaging of Carbonate Reservoirs and Systems, AAPG Memoir 81, p. 207-250.

Swart, P. K. (2008), Global Synchronous Changes in the Carbon Isotopic Composition of Carbonate Sediments Unrelated to Changes in the Global Carbon Cycle, Proceedings of the National Academy of Science, 105, 13741-13745.

Swart, P. K., and G. P. Eberli (2005), The nature of the d13C of periplatform sediments: Implications for stratigraphy and the global carbon cycle, Sedimen. Geol., 175, 115-130.

Connecting Outcrop to Subsurface: the Mixed Carbonate Siliciclastic System in the Neuquén Basin, Argentina (Year 2)

Michael Zeller, Klaas Verwer, Gregor P. Eberli, and Jose L. Massaferro[1]

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Project Purpose

Mixed carbonate siliciclastic reservoirs are highly complex systems with heterogeneous properties because of the intertwining of different facies and the often complicated diagenesis. Adequate reservoir characterization can only be achieved by integration of geometric, lithologic, and petrophysical data. The level of detail necessary to capture the small-scale variations of reservoir quality lies commonly below seismic resolution and therefore requires the incorporation of detailed outcrop observations with larger scale seismic interpretations. The aim of the proposed project is to combine outcrop and subsurface data for the development of a detailed model of the Upper Jurassic – Lower Cretaceous mixed carbonate siliciclastic system in the Neuquén Basin, Argentina. The depositional model aims to assess the processes and factors that control the mixing of the clastics and carbonates. The integration of the petrophysical data will place the reservoir characteristics into a geometrical framework.

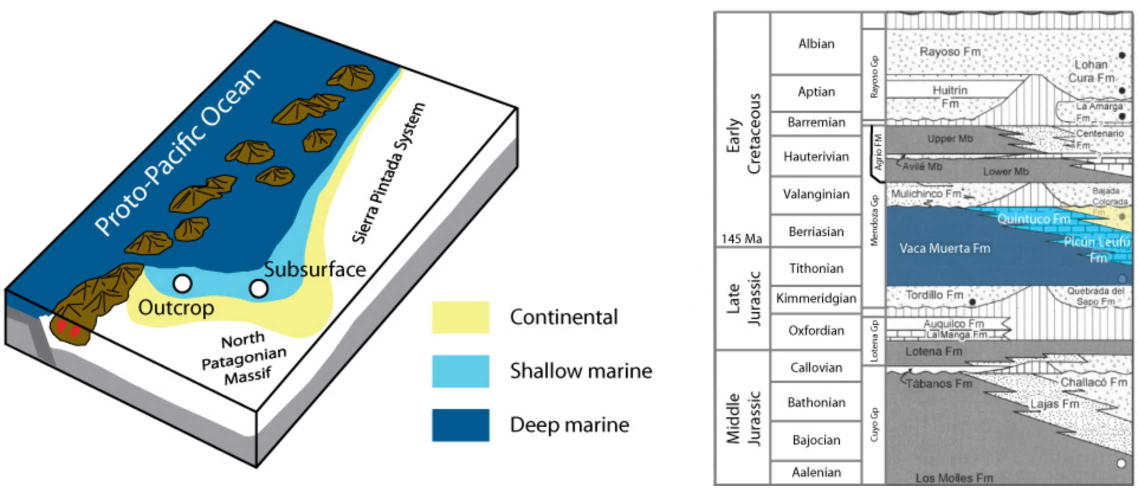

Figure 1. (Left) Paleogeographic setting of the Neuquén Basin with locations of subsurface and outcrop sections. (Right) Middle Jurassic to Lower Cretaceous stratigraphy of the Neuquén Basin, studied interval colored (both modified from Howell et al., 2005)

The studied interval comprises the prograding to aggrading mixed carbonate siliciclastic successions of the Quintuco Formation and the time equivalent basinal shales of the Vaca Muerta Formation (Fig. 1). These two formations form a mixed system that consists of a lower prograding unit composed of siliciclastics with a coarsening upwards trend (Fig. 2 top). The aggrading middle unit can be subdivided into a lower mixed carbonate siliciclastic interval capped by a clean carbonate interval which in turn is overlain by an aggrading upper unit in which siltstones and sandstones alternate with minor carbonates (Fig. 2).

Scope of Work

In year 1 we examined the lithologic character and the stratal architecture of Vaca Muerta – Quintuco Formations in outcrop. In addition, we evaluated several core intervals from a producing field in terms of sedimentological and petrophysical properties. Initial comparison of lithofacies character and geometries demonstrated general similarities in stratal architecture and lithology types of the outcrop and subsurface units.

In year 2 we plan to establish the sequence stratigraphic and chronostratigraphic correlation between the outcrop and subsurface data. This will help to understand the depositional system on a basin scale. The correlation will include the large-scale geometric analysis on seismic data and its comparison to geometries in outcrop (Fig. 2). In addition, the smaller scale outcrop observations will be integrated within the subsurface framework in order to better understand reservoir and flow barrier distribution.

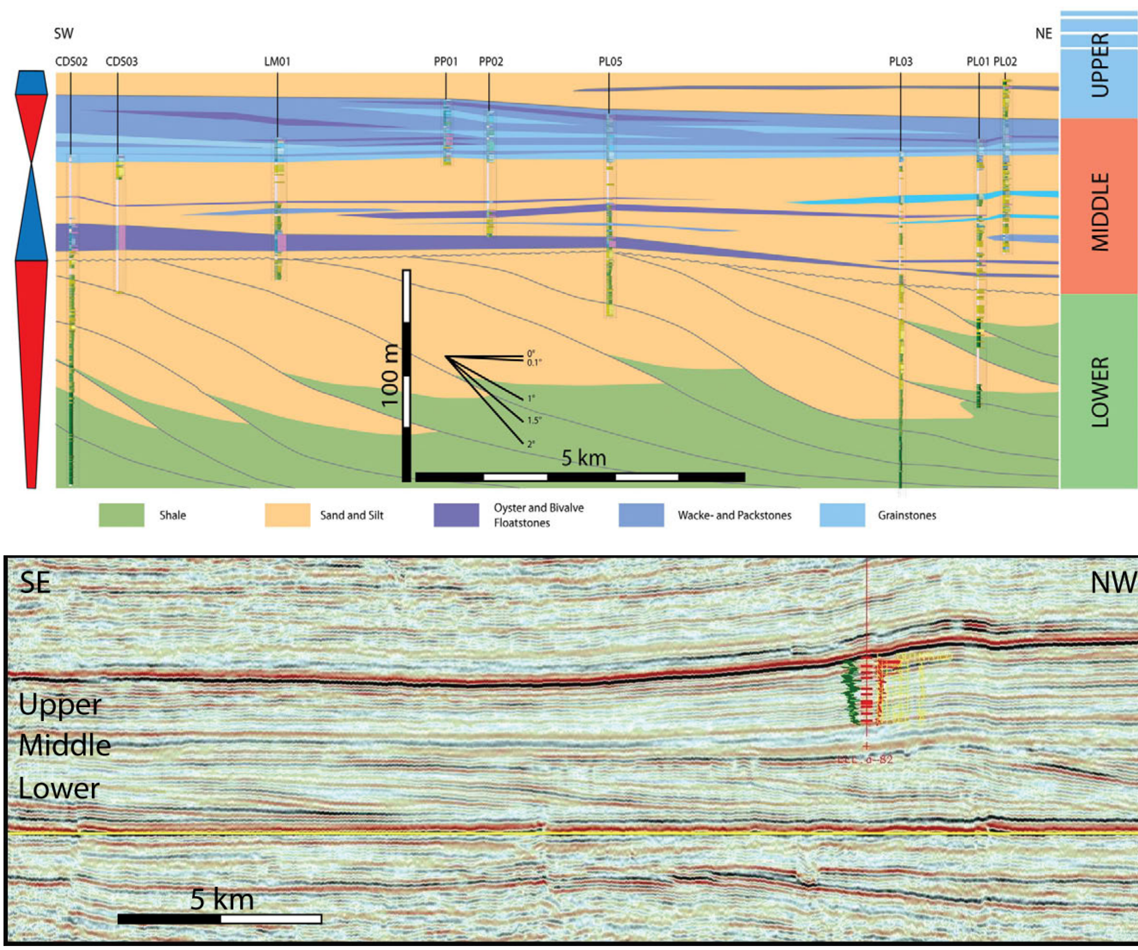

Figure 2. (Top) Outcrop correlation based on logged sections along a 15 km long cross section. (Base) Seismic Line from the Loma de La Lata Field. Note the architectural similarity of the units.

Key Deliverables

The combination of the seismic and subsurface core and log data along with the analysis of the reservoir scale architecture obtained of the outcrop will provide a comprehensive geological model of the mixed carbonate-siliciclastic Vaca Muerta - Quintuco system. The measured outcrop geometries and thicknesses together with subsurface geometries will provide the dimensions and distributions of the reservoir units within the prograding clinoforms and the aggrading topsets. The model can be used in order to enhance predictability of reservoir facies in this and other fields in comparable settings.

Project Description

The following tasks will be carried out:

1) Sr-dating of outcrop and subsurface samples will complement other studies that are based on biostratigraphy to establish the chronostratigraphic framework in both outcrop and subsurface.

2) Refined and extended seismic analysis to capture geometries and stratal architecture of the subsurface and to link outcrop to subsurface.

3) Basin wide cross sections based on mud log and well log data to understand carbonate - siliciclastic distribution throughout the basin.

4) Integration of outcrop reservoir geometries and subsurface framework.

Expected Results

The results of this project are expected to produce a geological model that will address two objectives:

1) The model will provide insight into the processes of mixing carbonate and clastic facies. In particular, it is expected to reveal the factors controlling the clastic dispersal in the basin and the cause(s) for the onset and end of the carbonate deposition.
2) The model will allow the prediction of reservoir facies distribution within the Upper Jurassic - Lower Cretaceous mixed carbonate siliciclastic system in the Neuquén Basin. Furthermore, the established sequence stratigraphic framework and the therein integrated analysis of reservoir scale heterogeneities will help to enhance reservoir predictability in other mixed carbonate-siliciclastic systems.

References

Howell, J.D., Schwarz, E., Spalletti, L.A., and Veiga, G.D., 2005. The Neuquén Basin: an overview. Geological Society of London, Special Publication, 252, 1-14.

Collation and Synthesis of Five Projects in the Mississippian Madison Formation

Gregor P. Eberli and Peter K. Swart based on the studies and in collaboration with Layaan Al Kharusi, Matthew R. Buoniconti, David A. Katz, Langhorne "Taury" Smith, and Hildegard Westphahl

Project Objectives

- Integrate the results of the sedimentologic, sequence and chemo-stratigraphic and tectonic analyses for a comprehensive model of the Madison ramp.
- Relate the results of the large regional studies to potential exploration plays and summarize the implications of local heterogeneities to production scale problems in the Madison ramp and carbonates in general.
- Outline the distribution, genesis, and petrophysical variability of reservoir quality dolomite within the Madison Formation.

Rationale

Taking the results of Sonnenfeld (1996) as a starting point, the CSL conducted five major studies in the Mississippian Madison Formation that addressed questions regarding a) the evolution of a carbonate ramp in a foreland basin setting, b) the sequences stratigraphic architecture in response to eustasy and diachronous subsidence, c) the formation and distribution of early and late diagenetic products in particular of reservoir-quality dolomite on the Mississippian ramp, d) causes and controls on petrophysical and reservoir heterogeneities within outcrop analogs and subsurface strata, and e) the relationship between high-resolution sequence stratigraphy and fracture patterns. The

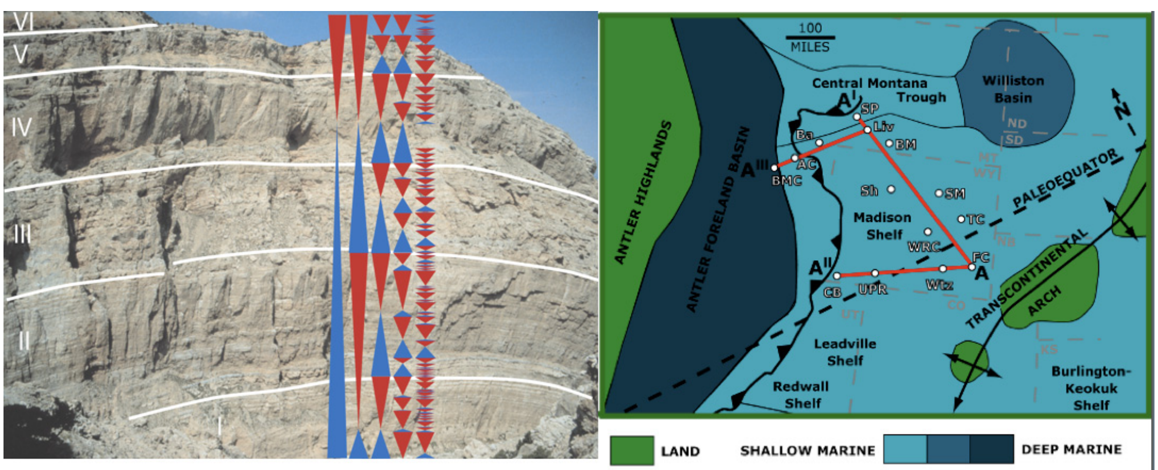

Figure 1. (Left) Madison Formation at Sheep Mountain Anticline with third-order sequence boundaries in white and the different orders of sequence stratigraphy indicated in transgressive (blue) and regressive (red) hemicycles. (Right) Location of the studied sections (white dots) and the regional cross-sections (red lines) constructed by Matthew Buoniconti and Davied Katz for the tectono-stratigraphic and geochemical investigations of the Madison shelf strata.

studies produced a wealth of results that are published in three dissertations, five journal publications numerous abstracts. Integrating the data sets is expected to reveal additional interconnections of processes and improve the results of the individual studies.

Overview of the Completed Studies

Matt Buoniconti extended the established sequence stratigraphic framework of the Madison Formation of Wyoming to the correlative Mississippian carbonate ramp, ramp margin, and basin strata of the central Montana trough and Antler foreland basin. The integrated sequence stratigraphy and geochemistry study of David Katz (2008) improved our knowledge of the formation and distribution of early and late dolomite. He traced the

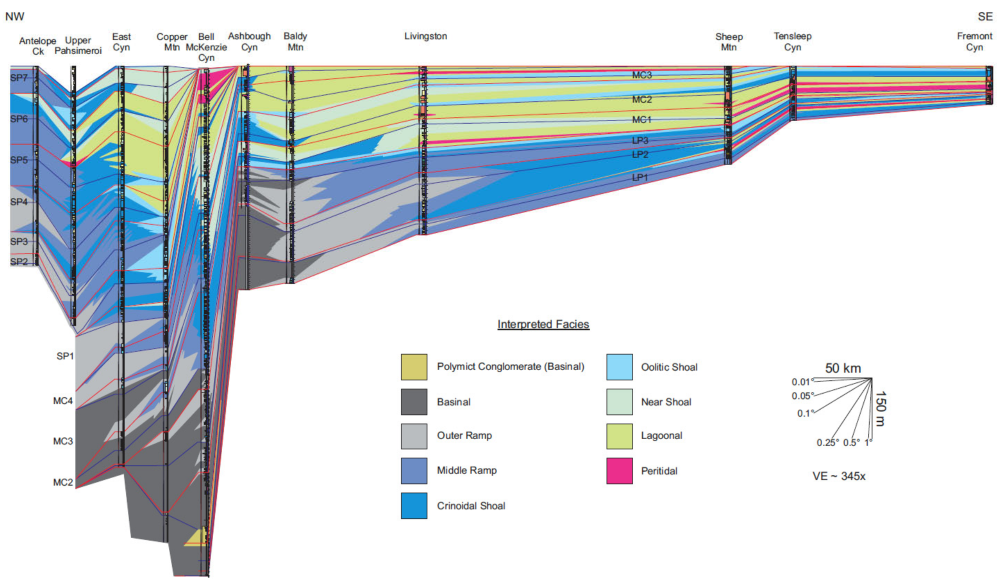

Figure 2. Super-regional cross-section from from extreme updip localities in Wyoming to extreme downdip locations in the Antler foreland basin of Idaho illustrating the overall architecture of the Madison Group and succeeding Scott Peak succession (Buoniconti 2008).

secular variations in the $\delta^{13}C$ values across the Madison shelf and refined the stratigraphic correlation between the measured sections. The detailed reservoir characterization by Westphal et al (1999) show how reservoir quality dolomite is related to the regional high-resolution sequence stratigraphic framework and how late stage hydrothermal diagenesis introduces lateral heterogeneity. Smith et al. (2004) explored this relationship in an exploration-scale study by testing the hypothesis that the reservoir quality dolomite occurs preferentially in the transgressive portions of sequences and cycles. Layaan Al-Kharusi (2009) documented how the fracture pattern also follows the high-resolution sequence stratigraphic framework.

Scope of Work

Although each of the studies in the Madison relied on the results of earlier and contemporaneous studies, the strength of all these data sets becomes clear after the completion of the three dissertations. In addition, rocks and samples collected in the studies described above were exploited in subsequent studies, in particular for petrophysical analysis of dolomites. These spin-off studies include the influence of the dolomite texture on acoustic velocity and the examination of porosity and permeability of the dolomites and coeval limestones. Some of these studies are published but some are not. There is a need to collate all the publications and reports. Thus, we plan to produce a Sedimenta CD with all this information. To facilitate the navigation to the different findings, a synthesis of the results will be included that will summarize and highlight the major results. Furthermore, a reference list of all publications that were produced by other groups during the last 10 years will be included to provide a comprehensive overview of the current knowledge of the Mississippian strata on the Madison shelf.

Deliverables

A volume of the Sedimenta Series on the Madison shelf with:

a) all the publications and dissertations of CSL students and scientists over the last 10 years,
b) a synthesis paper summarizing the results and implications, and
c) a comprehensive reference list of all the papers published in the last 10 years on the Madison.

References

Al-Kharusi, L.M., 2009, Correlation between High Resolution Sequence Stratigraphy and Mechanical Stratigraphy for Enhanced Fracture Characteristic Prediction. Unpub. Ph.D. dissertation, University of Miami, Coral Gables, 158pp. http://etd.library.miami.edu/theses/available/etd-11162009-190652/

Buoniconti, M. R., 2008, The Evolution of the Carbonate Shelf Margins and Fill of the Antler Foreland Basin by Prograding Mississippian Carbonates, Northern U.S. Rockies. Unpub. Ph.D. dissertation, University of Miami, Coral Gables, 456pp. http://etd.library.miami.edu/theses/available/etd-11262008-114526/

Katz, D.A., 2008, Early and Late Diagenetic Processes of Mississippian Carbonates, Northern U.S. Rockies, Unpub. Ph.D. dissertation, University of Miami, Coral Gables, 544pp. http://etd.library.miami.edu/theses/available/etd-09122008-110302/

Smith, L. B., Eberli, G. P., and Sonnenfeld, M.D., 2004, Sequence stratigraphic and paleogeographic distribution of reservoir-quality dolomite, Madison Formation, Wyoming and Montana. In: Grammer, G. M., Harris, P. M., and Eberli, G. P. (eds.), Integration of Outcrop and Modern Analogs in Reservoir Modeling. AAPG Memoir 80, p. 67-92.

Sonnenfeld, M. D., 1996, Sequence Evolution and Hierarchy within the Lower Mississippian Madison Limestone of Wyoming, in M. W. Longman, and M. D. Sonnenfeld, eds., Paleozoic Systems of the Rocky Mountain Region, Rocky Mountain Section SEPM, p. 165-192.

Westphal, H., Eberli, G.P., Smith, L.B., and Grammer, G.M., 2004, Reservoir characterization of the Mississippian Madison Formation, Wind River Basin, Wyoming. AAPG Bulletin, v. 88, p. 405-432.

3D VISUALIZATION OF FRACTURES,

KARST AND FLUID FLOW

Best Practice for Acquisition, Processing, and Interpretation of 3D GPR Data for Visualization of Deformation Bands, Fractures, and Karst in Carbonates

Mark Grasmueck and Pierpaolo Marchesini

Project Objectives

- Develop guidelines for optimal acquisition parameters of full-resolution Ground Penetrating Radar (GPR) data in fractured carbonates.
- Design the best processing suite for extracting fractures and karst from 3D GPR volumes.
- Propose a workflow for interpretation of GPR volumes with fractures for enhaced visualization of structural features and karst.

Rationale

Using a newly developed GPR system with the capability of efficiently acquiring high-resolution data at centimeter precision (Grasmueck and Viggiano, 2007)), we have imaged fractures, deformation bands, and karst features in porous and tight Cretaceous carbonates. The partitioning of the rock by fractures and karst at and below the GPR wavelength, thin vertical fractures and irregular karst features and a faint stratigraphy present a challenging task for GPR imaging. A crucial aspect of fracture imaging is to design surveys with the optimal grid density, frequency and antenna polarization to collect un-aliased data with high-information content (Fig. 1).

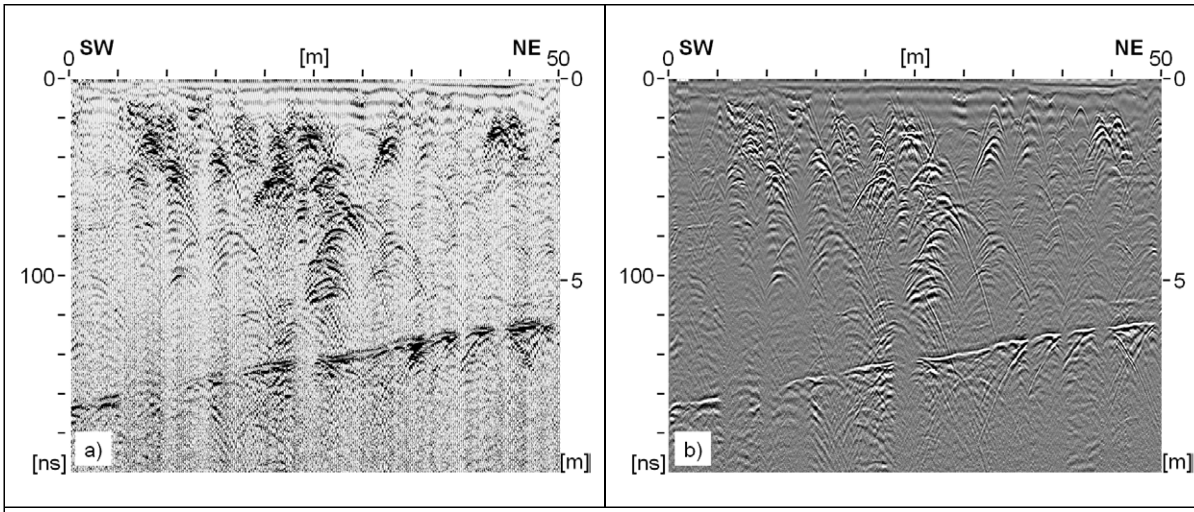

Figure 1. Vertical fractures and irregular karst features produce diffraction cones of variable clarity depending on the trace spacing. 200 MHz GPR profile acquired with a) half-wavelength trace spacing of 20cm and b) eighth-wavelength trace spacing of 5 cm. Depth scale is based on 9.75cm/ns.

Equally important is to apply an appropriate processing suite, including 3D migration that aligns the diffraction apices in vertical fracture planes and cluster of karstic dissolution features (Fig. 2). Final fracture visualization relies on using the best attribute in the interpretation packages. The aim of this project is to use different survey designs, processing and interpretation suites to develop a much-needed guideline for optimal imaging of fractures and karst in three dimensions.

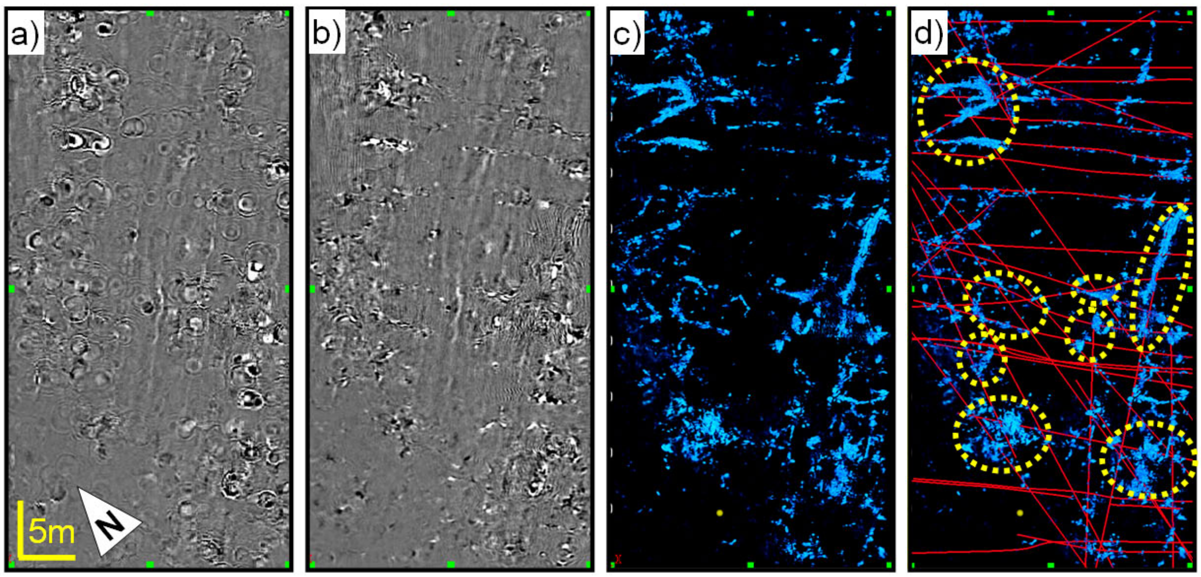

Figure 2. Topview of horizontal slice through 3D GPR cube extracted at 1.95 m depth in the Solvay quarry near Cassis, France. (A) Unmigrated data with abundant diffraction circles. (B) 3D migrated (C) Volume rendering of part of 3D migrated cube ranging from 0 to 2.50 m depth. Low amplitudes are set transparent and the higher amplitude anomalies show in shades of blue. (D) Interpretation overlay shows how focused diffractions are aligned in vertical fracture planes. High amplitude clusters are interpreted as karst features.

Scope of Work

To decide on the optimal acquisition parameters we will analyze several survey designs in which the trace spacing, the frequency, and the antenna polarization were changed. We will discuss the advantages and disadvantages for each design. Processing of the different cubes will provide additional information for the best survey design. Different processing suite will evaluated to optimize the resolution of the fracture imaging. A crucial step is the visualization in interpretation software. Initial results indicate that choosing the appropriate attribute(s) will improve the visualization of the fractures and karst and, thus, the accuracy of the structural analysis.

References

Grasmueck, M. and D. A. Viggiano, 2007, Integration of Ground-Penetrating Radar and Laser Positioning Sensors for Real-Time 3-D Data Fusion. IEEE Transactions on Geoscience and Remote Sensing, vol. 45, n. 1, January 2007.

Intergration of 3D GPR and Outcrop Analysis of Solution Enhanced Fractures and the 3D Visualization of Karst Cavities by GPR (Cassis, France)

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Rationale

Characterizing fracture patterns of reservoirs in the subsurface is a challenging task that requires a good understanding of the 3D geometry and distribution of the fractures as well as the processes controlling the distribution of fractures. Fracture characterization in outcrops relies mostly on scan line measurements to capture the properties of fractures including the type, orientation, length, aperture, spacing, density and fracture termination. The inability of this technique to visualize and analyze the fracture in three dimensions, however, limits the fracture characterization using this method. Likewise the 3D distribution of karst cavities is not discernable in outcrops but is of paramount importance for fluid flow in the subsurface. This study takes advantage of newly developed high precision and high resolution 3D GPR (Grasmueck et al., 2005) to image in 3D both fractures and the karst cavities in the shallow subsurface.

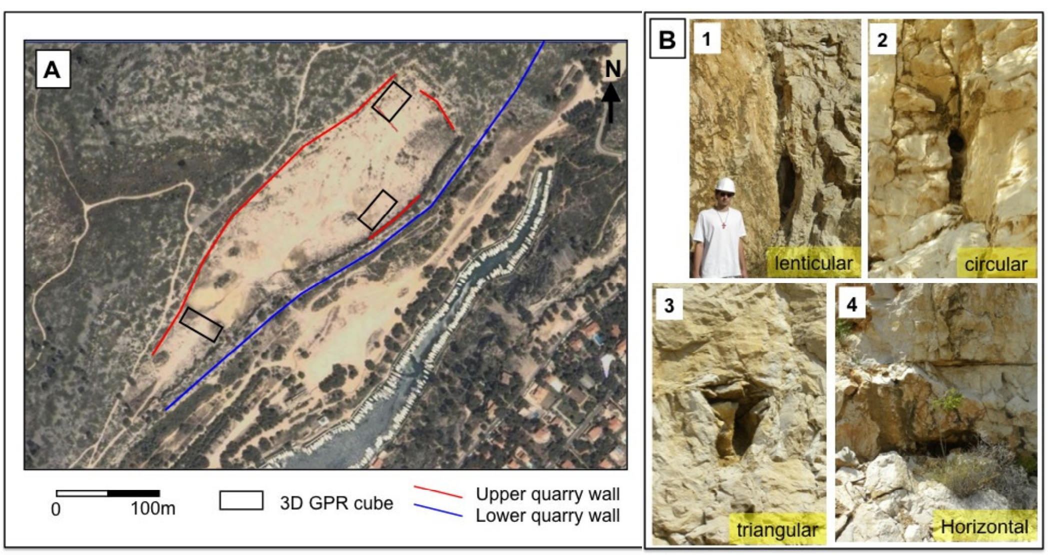


Figure 1. (A) Aerial view of the Solvay quarry near Cassis. The quarry is approximately 500m long and 100 – 200 m wide. Three 3D GPR cubes were acquired in key locations and fracture analyses were performed along the quarry walls. (B) Karst of various size and shape are observed in the outcrop mostly along fracture and bedding planes.

Scope of Work

Late Barremian shallow-water carbonates strata in the quarry located near Cassis,

France are dissected by four families of steep mostly open fractures. Many fractures are solution enhanced and karst cavities form along the fracture and bedding planes (Figure 1).
The geometry, the character and the distribution of the fractures in three dimensions are investigated in an integrated method of outcrop and 3D GPR analysis. Likewise the distribution of the karst cavities in outcrop has been documented. The next step is the integration and correlation of the different data sets to produce a comprehensive 3D characterization of the fracture and karst network (Figure 2). In addition, a stratigraphic, diagenetic and petrophysical analysis will be performed to assess the controlling factors for fracture and karst formation.

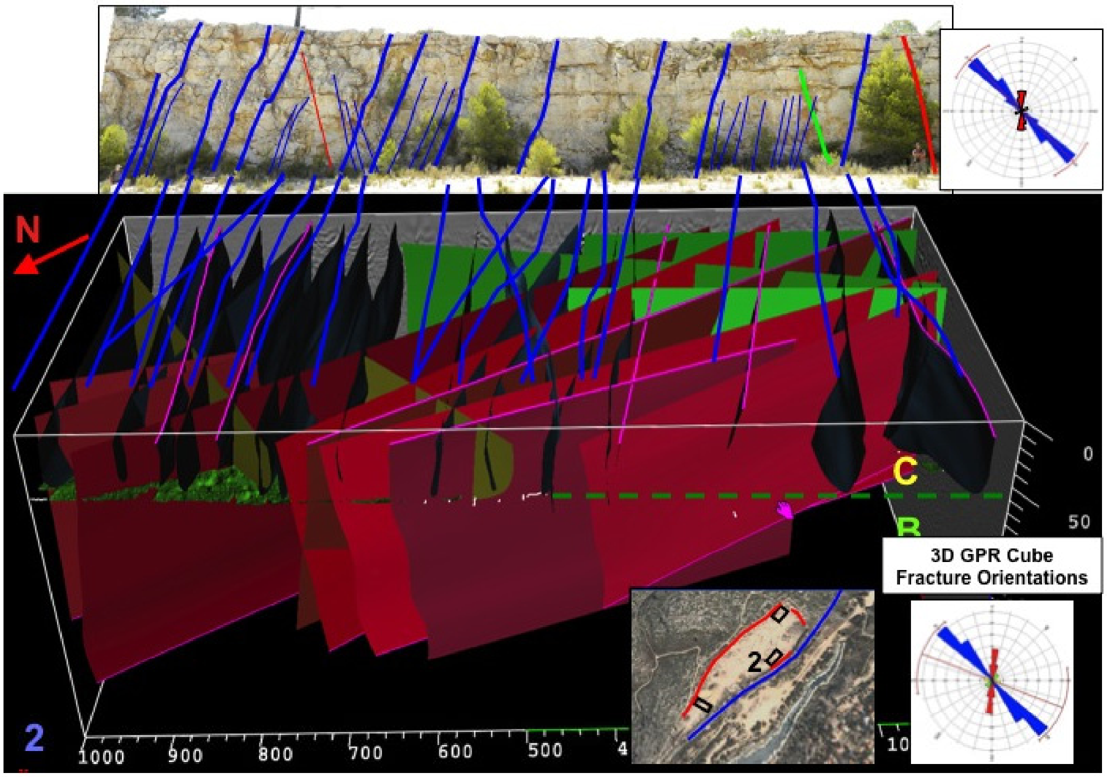


Figure 2. Comparison between fractures in 3D GPR cube 2 and the adjacent quarry wall. There is an excellent match in the orientation and the density of the fractures.

Method

Conventional scan line method is used to assess the fracture properties and 2D distribution along the quarry walls, whereby the fracture type, position, orientation, length, aperture, spacing, termination and density are recorded. Three 3D GPR cubes at key locations record the fractures and karst features in the subsurface. A processing and interpretation workflow is developed to isolate both the fractures and karst in the GPR data. Landmark 3D modeling software and its attributes are used to visualize the fractures, stratigraphy and karst features (Figure 2).

The stratigraphic sections are divided into sequence stratigraphic units surfaces correlated into the GPR data (Coll et al., 2009). Thin sections provide relevant facies and diagenetic information of the strata. Petrophysical measurements, including porosity and both compressional wave and shear wave velocity give indications of the stiffness variations in each stratigraphic unit. Stable isotope analyses of the speleothems within the karst cavities will help assess how many different karst episodes produced the observed karst.

Key Deliverables

1. Visualization and quantification of 3D distribution of the fractures and karst in the GPR cubes.
2. Integrated outcrop-subsurface structural analysis and a comparison of the outcrop versus the GPR analysis.
3. Analysis of karst features, including their distribution in three dimensions, the timing of the karstification, and their relationship to the fractures.
4. Quantitative assessment of the karst volume within the GPR volumes.
5. Static reservoir model that takes into account the stratigraphic, fracture and karst information and the matrix porosity and fracture/karst porosity.

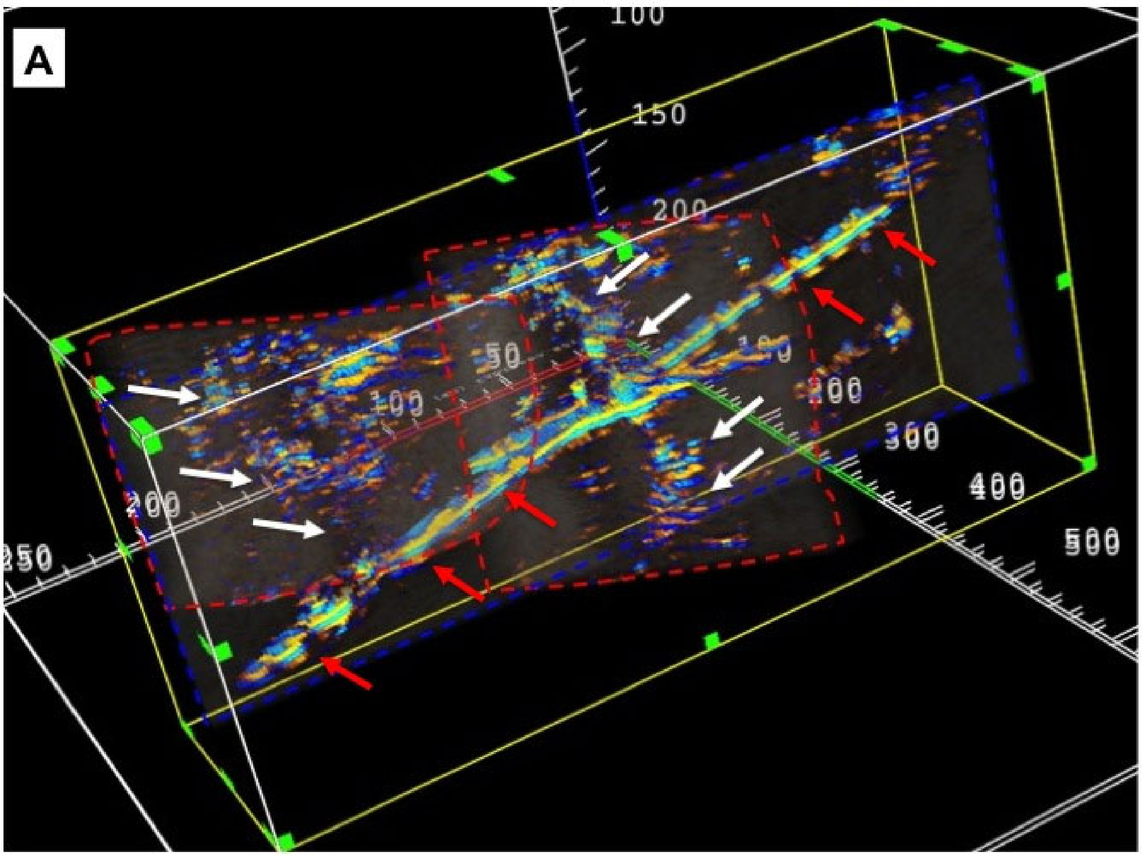


Figure 3. The fractures and karst are high-amplitude features in the GPR volumes. A semi-transparent amplitude rendering of the fracture planes displays the stratigraphic boundary (red arrows) and the karst feature (white arrows). We will develop a workflow to visualize and quantify the karst in 3D.

Expected Results

The results of this research are expected to provide a workflow for an accurate technique to characterize solution-enhanced fractures and associated karst in the outcrop and the shallow subsurface. In addition, this data set will for the first time image the 3D distribution of fractures and the associated karst, which will allow answering questions in regards to the mutual relationship between the two processes. A good understanding of the 3D geometry and distribution of the fractures and karst will allow us to make a more comprehensive reservoir characterization of fractured limestone reservoirs.

References

Coll et al., 2009, Integration of GPR, LIDAR and conventional outcrop data for accurate multi-scale geometry in fractured reservoirs. CSL Prospectus 2009.

Grasmueck, M., Weger, R., and Horstmeyer, H., 2004, Full-resolution 3D GPR imaging. Geophysics, v. 70, p. K12–K19.

Time-lapse 3D GPR for Fluid Flow Quantification in Fractured Carbonates: Cretaceous Orfento Formation, Madonna della Mazza, Italy

Pierpaolo Marchesini, Mark Grasmueck, and Gregor P. Eberli

Project Objectives

- Quantify water content changes and track flooding/drainage boundaries as the response to a controlled infiltration experiment in fractured carbonates.
- Calculate flow propagation rates within porous matrix and quantify influence of faults and deformation bands on flow.
- Mass-balance checks of moving fluid to verify water content changes computations.

Rationale

Currently, the characterization of fluid flow mostly relies on laboratory sample measurements, upscaling, and modeling. In this study we use for the first time 4D Ground Penetrating Radar (GPR) to monitor in-situ fluid flow in response to a controlled water infiltration experiment at an outcropping fractured carbonate reservoir analog. 3D GPR images in great detail show the fractures, faults, and deformation bands in the Cretaceous Orfento Formation in the Madonna dell Mazza quarry in Italy (Fig. 1). Because GPR is sensitive to changes in subsurface water content, it can be used to monitor propagation fronts represented by wetting and drying events. Variations detected in the GPR signature between time-lapse data can be linked to zones where water content changes occurred (Truss et al., 2007). Quantification of fluid flow within a network of faults and deformation bands helps the flow prediction models and residual fluid recovery.

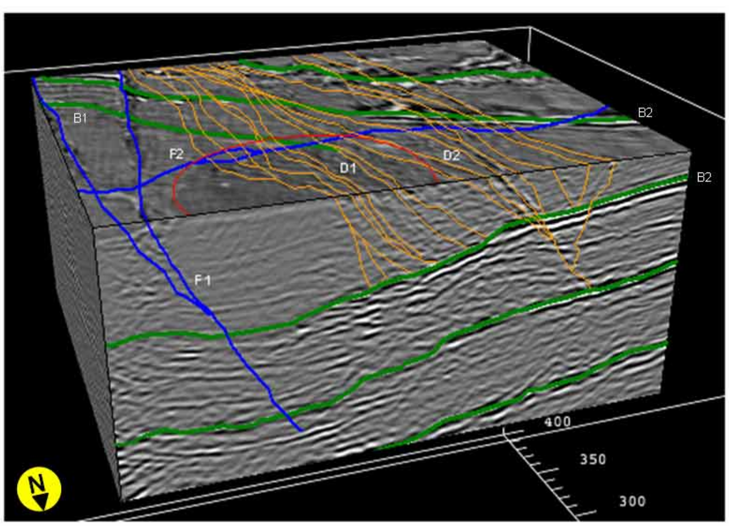


Figure 1. Three dimensional schematic interpretation of the main geological features within the GPR volume: dipping beds B1 and B2, fractures F1 and F2, clusters of deformation bands D1 and D2. The red circle indicates the area where the temporary pond was installed.

Background and Methodology for 2009 Fieldwork

In summer 2009 we performed a series of 3D GPR surveys before and after a controlled water infiltration to determine and quantify the influence of faults and deformation bands on fluid flow in a porous matrix. A temporary polyethylene pond of 4 m diameter was installed on the quarry floor and 3000 liters of water were infiltrated over 30 hours. The first post-infiltration GPR survey was acquired as soon as there was no more standing water and after the pond walls were removed. Overall, sixteen 3D GPR time-lapse surveys were conducted monitoring a 20x20x10 m volume: 2 surveys before (dry) and 14 surveys after the water infiltration (wet) tracking fluid flow over a period of 5 days.

Preliminary Results

When comparing pairs of 3D GPR data cubes, arrival time shifts for GPR reflections are caused by water content changes. A volume-warping algorithm extracts the intrinsic time shifts between pairs of GPR data cubes visualizing snapshots of flow direction and intensity (Fig. 2). In addition, gradients of time shifts provide information about how faults and deformation bands influence fluid flow with respect to the surrounding porous matrix.

Scope of the 2010 Project

Preliminary results are encouraging but yet the 16 volumes still have a wealth of information that has to be exploited: A total of 105 combinations of pairs of repeated surveys can be used to calculate intrinsic time shifts and track flow with time increments between 2 hours and several days. However, time-lapse 3D GPR processing is computationally demanding and the average time for full-density warp calculation for just one survey pair is 8 days. In order to reduce the compute times by a factor of 10 or more, we are in the process of implementing the warp code on a GPU processing unit. Once this computation bottleneck is removed, the analysis of the comprehensive 4D GPR dataset recorded at the Madonna della Mazza quarry should become more feasible.

The goal of this GPR study is to achieve a full characterization of the subsurface fluid flow in terms of:

1) Water content changes and tracking of flooding/drainage boundaries. Application of the Topp petrophysical transfer function to time shift volumes (Topp et al., 1980) quantifies the in-situ water content changes over time and space. Estimation of the extent of the wetting bulb will be achieved by comparing the dry initial state with the fourteen GPR surveys recorded over the following 5 days. Moreover, to characterize the dynamics of wetting, saturation, draining, and surface evaporation, we can compare pairs of repeat 3D GPR surveys recorded within a 2-3 hr interval to receive snapshots of the fluid flow over such short timeframes (Fig. 3). This dataset is unique as it consists of a continuous series of

GPR surveys where the total amount of infiltrated water moving through the porous rock volume is known.

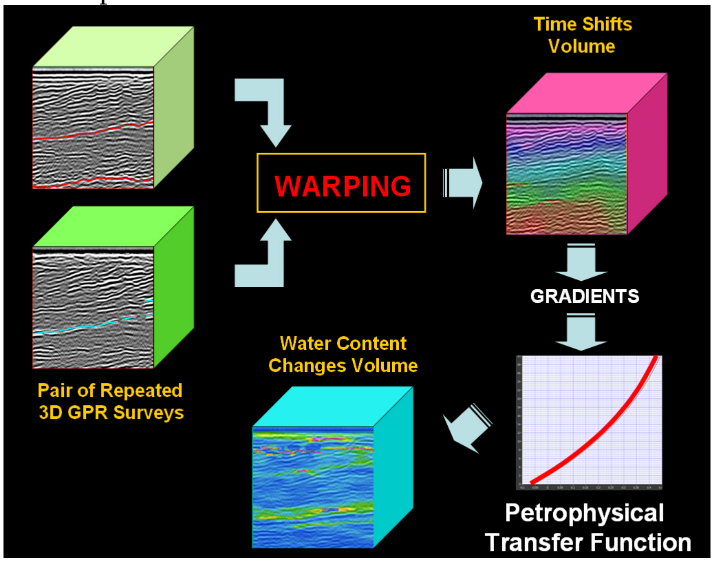


Figure 2. Warping extracts the intrinsic time shifts between pairs of time-lapse volumes. Application of the Topp petrophysical transfer function yields volumetric water content changes over time and space.

2) Flow propagation rates through major fluid conduits and the porous surrounding matrix. With a semi-transparent rendering of the water content change volumes over the regular 3D GPR data, the hydraulically most active faults and deformation bands can be identified together with a quantification of fluid transport within these zones.

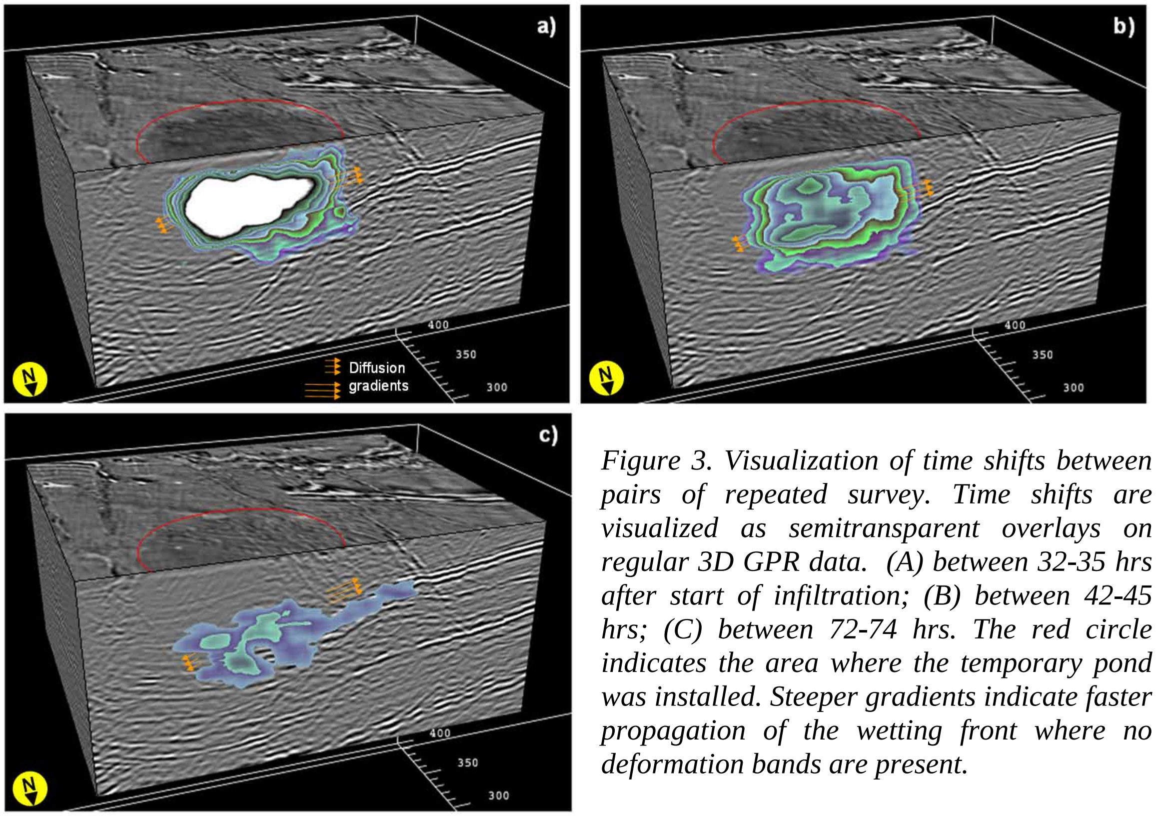


Figure 3. Visualization of time shifts between pairs of repeated survey. Time shifts are visualized as semitransparent overlays on regular 3D GPR data. (A) between 32-35 hrs after start of infiltration; (B) between 42-45 hrs; (C) between 72-74 hrs. The red circle indicates the area where the temporary pond was installed. Steeper gradients indicate faster propagation of the wetting front where no deformation bands are present.

3) Fluid mass balance used to verify the water content change computations. In our previous 4D GPR experiments conducted within the Miami Oolitic Limestone, mass balance calculation showed that volumetric water content change estimates from 4D GPR datasets are accurate within a few percent.

4) Compare time-lapse GPR results with conventional infiltration and evaporation measurements performed in the field and on samples

Key Deliverables

Integrate water content change volumes, propagation rates, quantification of fluid mass balance, conventional 3D GPR data, and rock sample measurements to fully characterize stratigraphic-structural-hydraulic relationships at the Madonna della Mazza Quarry. This pilot project also introduces a workflow applicable to other outcropping reservoir analogues where a precise understanding of flow processes is needed.

References

Topp, G.C., Davis, J.L. and Annan, A.P., 1980, Electromagnetic determination of soil water content: Measurements in coaxial lines. Water Resour. Res. 16: 574–582.

Truss, S., Grasmueck, M., Vega, S., and Viggiano, D.A., 2007, Imaging rainfall drainage within the Miami oolitic limestone using high-resolution time-lapse Ground Penetrating Radar, Water Resources Research, Vol. 43, No. 3, W03405, doi: 10.1029/2005WR004395.

LABORATORY EXPERIMENTS IN PETROPHYSICS

Petrophysical Characterization of Plio-Pleistocene Reef Systems in the southern Dominican Republic

Albertus Ditya, Klaas Verwer, Gregor P. Eberli, and James S. Klaus

Project Purpose

The Pleistocene reefs that developed in the Dominican Republic over the past 1.8 million years provide a unique opportunity to study the complex three-dimensional architecture and controlling factors of fringing reef development during high frequency sea level cycles (see prospectus by Klaus et al.). Coral reefs present special challenges for geological and geophysical studies because reef growth is highly variable even over a small spatial scale (Jordan and Wilson, 1998). A dedicated ground-truth data set needs to be developed for assessing the variability in petrophysical properties in the reef rocks.

Scope of Work

Generally, carbonate systems are difficult to image using reflection seismic technologies due to their spatially highly variable acoustic properties as a result of their intrinsic pore systems during evolution and diagenetic overprint. Only the facies transitions of reefs to surrounding depositional environments are usually visible on high quality seismic imagery. As a result, internal reflections of reef bodies are mostly incoherent and lack information on internal anatomy and spatial distribution of physical properties. To advance the understanding of the acoustic and hydraulic behavior of such complex systems, we aim to measure a full data set of the Pleistocene carbonate rocks from the Southern Dominican Republic for petrophysical properties.

Key Deliverables

This project will provide an overview of the factors controlling petrophysical properties in carbonate reefs from the Dominican Republic. In addition, we will assess the influence of both the complicated textures and pore types on the velocity-porosity and porosity-permeability relationships.

Project Description

We have collected fourteen one meter cores and sixteen hand samples from different terraces, which represent various carbonate lithologies, depositional environments, and diagenetic processes (Figure 1). Each of these cores and samples will be selectively plugged based on different lithologies and depositional environments for further measurements and thin sections. Subsequently the following workflow will be applied:

- Cut thin sections for rock and pore typing and digital image analysis.
- Conduct petrophysical measurements (acoustic velocity, porosity, permeability).
- Generate a catalogue that captures the relationships between geological parameters and petrophysical properties.
- Finally, integrate the results with the results from the geophysical imaging.

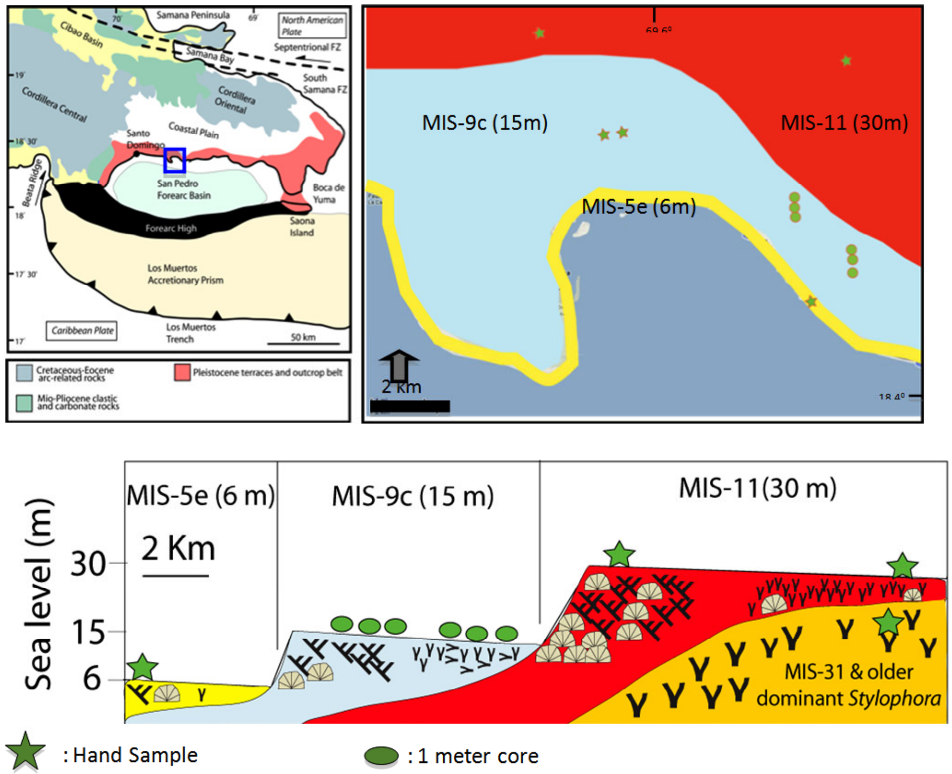


Figure 1. (Top) Regional geologic map. Blue inset corresponds to maps of various documented terrace elements. Tentative ages have been ascribed and referred to as marine isotope stage (MIS). (Bottom) Cross-section through the terraces showing the sample locations (stars are hand samples; circles are one meter cores).

Expected results

The geological and geophysical data will provide a 2D high-resolution model of the reef architecture aiming to reveal internal geometries as a function of the spatial evolution of the reef system. The petrophysical experiments will enhance insight in key parameters controlling acoustic properties in reef environments, such as pore type size and distribution, and provide a comprehensive understanding of the variability of both acoustic and hydraulic properties in these reef systems.

References

Jordan, C and Wilson, J.L., 1998 Reefs: Geologic considerations for geophysicists, The Leading Edge, no. 3 p. 325-328

The Importance of Early Cements in Maintaining Porosity and Permeability during Burial

Rosely A. Marçal, *Gregor P. Eberli, Adali R. Spadini*[1], *and Antonio C. Soares*[1]

[1]*Petrobras, Rio de Janeiro, Brasil*

Project Purpose

Understanding the factors that sustain good porosity and permeability values in the subsurface is still a problem. Rock mechanics experiments show that even applying pressures in simulation to real burial depth, carbonate rocks can maintain good reservoir quality, and some permeability was maintained even after increasing the compaction until the pores collapsed. Our working hypothesis is that cementation during the early diagenesis is the main factor for sustaining the reservoir quality porosity and permeability at great depth. To test this hypothesis, we plan compaction experiments of modern sediments and Pleistocene samples with different amounts of cementation to assess the decrease of this 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 selected Pleistocene oolitic peloidal grainstones and packstones from six cores on Great Bahama Bank (Ocean Cay, Andros Island, New Providence, Cat Island, Long Island, and Eleuthera Island). The analyzed facies consist of oolitic, peloidal, and skeletal grainstones, partially cemented with 5 - 20% of marine and meteoric cementation. The meteoric cements are equant spar crystals forming a fringe around the grains or filling the pore throats as meniscus. Marine diagenesis occurred as an isopachous fringe and micrite cement filling the pore throat forming a meniscus texture. Compaction experiments are simulating the evolution of permeability from the surface to the equivalent of 3,000 meters (approximately of 69 MPa) and 5,000 meters of burial depth (approximately of 127 MPa). We are simulating 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 and we will measure the capillary pressure using Hg injection (P_{Hg}) and perform micro-tomography. 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.

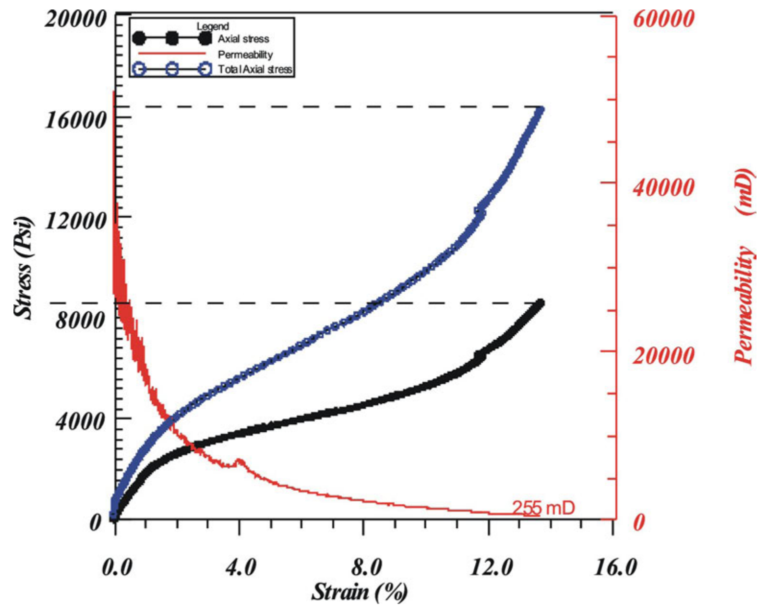


Figure 1. Stress versus strain and permeability of an ooid sample. Permeability (thin red line) abruptly increases at 4% of strain, which is probably caused by micro-fractures that start to develop. The decreasing permeability with increasing stress indicates that these micro-fractures close with increasing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

The petrophysical values of the Pleistocene rocks after the compaction experiment will be compared to the Albian rocks from to Brazilian basins at different burial depths. In addition we will compare the similarity of the early diagenesis and facies at the Albian cores with the early diagenesis and facies at the Pleistocene cores. The samples for this comparison are from the Campos Basin at 2,700 meters of burial depth and Santos basin at 5,000 meters of burial depth, respectively. We will describe and quantify the amount of cement, type of pores, and compare the petrophysical values of the Pleistocene rocks after the compaction experiment with Albian rocks from the Brazilian Basins.

Key Deliverables

This project will provide diagenetic characterization and integrated petrophysical dataset on Holocene and Pleistocene carbonate rocks with a thorough determination of the vertical heterogeneities of these deposits. The integrated dataset will provide a comprehensive diagenetic model of these rocks with porosity, permeability, and acoustic characteristics. This diagenetic model will be used in comparison with other oolitic reservoirs at different depths.

The dataset will be available to the Industrial Associates and can be used to evaluate variations in petrophysical parameters that feed geologic or simulation models for carbonate reservoirs.

Electrical resistivity, Archie's Law and Pore Space Geometry in Carbonates

Klaas Verwer, Gregor P. Eberli, and Ralf J. Weger

Project Purpose

The electrical resistivity in fluid-filled sedimentary rocks is largely controlled by its pore space geometry, as the electric current is conducted predominantly through the pore fluid. Yet, in carbonates, the variation in electrical resistivity and the cementation factor for a given porosity are poorly understood. Many studies have recognized that acoustic velocity and permeability in carbonate rocks is dependent upon pore geometry. In this study we aim to explore the complex relationship between the shape and size of pores and pore throats and the flow of the electric charge. It is postulated that the carbonate pore structure exerts a strong control on the electrical resistivity.

Scope of Work

Initial laboratory measurements of electrical resistivity in relation to quantitative geometric parameters derived from digital image analysis of thin sections yielded unexpected but strong correlation with the geometrical parameter *m* of Archie's law (Archie, 1942) that is derived from resistivity properties of the rock. For example, samples with a highly intricate pore network have a low formation resistivity factor and, thus, a low cementation factor for a given porosity. Furthermore, some samples with a high cementation factor had an unexpected high permeability. To corroborate these results and consolidate the initial trends, we aim to expand the data set with a sample set containing a variety of different textures and pore types.

Key Deliverables

This project will provide an overview of the factors controlling electrical resistivity in carbonate rocks. In addition, we will assess the influence of both the complicated textures and pore types on the electrical resistivity-porosity and porosity-permeability relationships.

Project Description

The project will utilize the following workflow:

1. Electrical resistivity, formation factor, and porosity were measured on 33 1" and 1.5" core plug samples. Four-electrode resistivity was measured as a function of frequency, stress, and temperature.
2. Perform CSL digital image analysis on thin sections to assess pore structure (Weger et al., 2009).
3. Evaluate scatter in resistivity measurements as a function of the carbonate pore structure and other physical properties such as permeability.
4. Test obtained relationships within Archie's Law and generalize the obtained results.

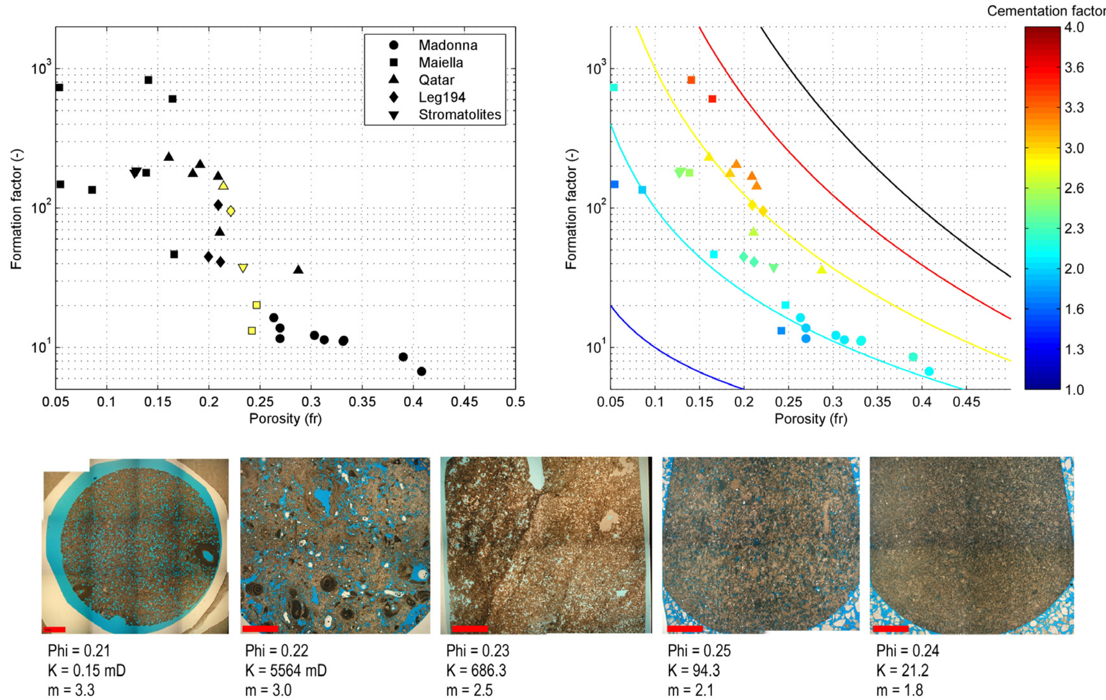


Figure 1. Cross plot of porosity vs. formation factor (left) and porosity vs. formation factor with the cementation factor (m) superimposed. Also shown are lines of equal m (right). Resistivity decreases with increasing porosity. The formation factor shows a variation of one order of magnitude for a given porosity. The cementation factor ranges from 1.75 to 3.5 in the data set. Porosity, gas permeability, cementation factor, and corresponding photomicrographs are shown (yellow symbols).

Expected results

The project aims to elucidate the effect of the carbonate pore structure on electrical resistivity in carbonates. The previously documented strong correlation of quantitative geometric parameters derived from DIA of thin sections to the geometrical parameter *m* of Archie's law that is derived from resistivity properties of the rock will be consolidated and generalized. The connection potentially allows pore structure and permeability to be inferred from down hole log information as long as the fluid characteristics are known. In addition, if the initial results hold up, it will have drastic implications for the calculations of water saturation (S_w) from resistivity logs.

References

Archie, G.E., 1942, The electrical resistivity log as an aid in determining some reservoir characteristics: Petroleum Transactions of AIME (Am. Inst. Min. Metall. Eng.), v. 146, p. 54-62.

Weger, R.J., Eberli, G.P., Baechle, G.T., Massaferro, J.L., and Sun, Y.-F., 2009, Quantification of pore structure and its effect on sonic velocity and permeability in carbonates: AAPG Bulletin, no. 10, v. 93, p. 1297-1317.

EXPLORATION OF NEW GEOCHEMICAL TOOLS

Clumped Isotopes: Application to Diagenesis

Peter K. Swart

Project Purpose

The recognition that clumped isotopes of CO_2 are solely dependent upon temperature and not on the isotopic composition of the fluid from which they are formed has opened significant possibilities in unraveling the temperature and water signal as applied to diagenetic carbonates. The purpose of this project will be to investigate this technique as applied to sedimentary carbonates.

Instrumental Requirement

The first step in performing clumped isotope measurements is the acquisition of an instrument capable of simultaneously measuring mass 44-47. The instrument must also have very sensitive amplifiers at mass 47-49 (to measure the species at these masses). This instrument is being purchased courtesy of a grant from the National Science Foundation and matching financial support from the CSL and the Stable Isotope Laboratory. Once the instrument is installed and works satisfactorily, we will develop procedures to extract the CO_2 from carbonate samples and subsequently purify it without fractionation.

Figure 1. Mass spectrometer able to measure clumped isotopes. The instrument has four collectors and sensitive amplifiers that allow measuring the species at the 44-49 masses.

Project Background and Goal

Ghosh et al. (2006) demonstrated then that the abundance of $^{13}C^{18}O^{16}O$ in CO_2 generated from the classical reaction of carbonates with phosphoric acid, is proportional to the abundance of $^{13}C^{18}O^{16}O_2{}^{2-}$ ion species within the minerals. Usually, abundances of mass 47 CO_2 are reported using the variable $\Delta 47$ representing the difference in permil between the measured 47/44 ratio and the expected 47/44 ratio for that sample if its carbon and oxygen isotopes were randomly distributed among all isotopologues. Using this nomenclature any differences in the $\delta^{13}C$ or $\delta^{18}O$ of the water from which the mineral precipitated is taken care of by the expected 47/44 ratio and therefore the difference ($\Delta 47$) is solely dependent upon temperature. To date, this method has been applied to a number of different carbonate systems (Affek, et al., 2008a; Affek, et al., 2008b; Ghosh, et al., 2007a; Ghosh, et al., 2007b), but not been investigated in the service of diagenesis. The first goal of this study will, thus, be to evaluate whether the clumped isotope technique can be applied to diagenetic applications.

Scope of Work

Following the delivery of a new mass spectrometer which is capable of measuring the abundances of masses 47-49, we will start to investigate the clumped signature in naturally occurring carbonates whose temperature of formation is well constrained. In addition, we will artificially produce carbonates at higher temperature in order to ascertain the temperature dependence of the $\Delta 47$ signal in these materials.

Key Deliverables

1) Assessment of whether the clumped isotope technique can be applied to diagenetic applications.
2) Assessment of temperature dependence of the $\Delta 47$ signal in carbonates.

References

Affek, H. P., et al. 2008a, Glacial/interglacial temperature variations in Soreq cave speleothems as recorded by 'clumped isotope' thermometry, Geochim. Cosmochim. Acta, 72, 5351-5360.

Affek, H. P., et al. 2008b, 'Clumped isotopes' in speleothem carbonate and atmospheric CO2 - Is there a kinetic isotope effect? Geochim. Cosmochim. Acta, 72, A6-A6.

Ghosh, P., et al. 2006, C-13-O-18 bonds in carbonate minerals: A new kind of paleothermometer, Geochim. Cosmochim. Acta, 70, 1439-1456.

Ghosh, P., et al. 2007a, Calibration of the carbonate 'clumped isotope' paleothermometer for otoliths, Geochim. Cosmochim. Acta, 71, 2736-2744.

Ghosh, P., et al. 2007b, Carbonate clumped isotope thermometry of molluscs and its applications to Pleistocene gastropod fossils from South Dakota, Geochim. Cosmochim. Acta, 71, A319-A319.

Sulfur Isotopic Composition as a Tool for Understanding Dolomitization: Application to Ancient Examples

Peter K. Swart and Samantha Evans

Project Purpose

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 a possible diagenetic tool to understand the paragenesis of certain carbonates in particular dolomites and carbonates formed in high temperature.

Scope of Work

The project initially developed the equipment necessary to process the samples for the stable S isotopic analyses. This work has been largely completed in 2007 and 2008. In 2009, we presented data from a core retrieved in the south Australian Bight during Leg 182 in an extreme environment, which possesses very high concentrations of hydrogen sulfide, regions which have very little sulfate, and others with very high sulfate. In 2010 we will continue to work on the Leg 182 sites (Figure 1) as well as applying the techniques to two older dolomite occurrences, the Mississippian Madison Formation (Katz et al., 2007; Katz et al., 2006; Westphal et al., 2004) and the Pliocene dolomites from San Salvador (Dawans and Swart, 1988) in the Bahamas.

Key Deliverables

The analytical procedure and workflow for the use of $\delta^{34}S$ of CAS to ascertain the nature of the diagenetic environment, i.e. open marine, closed marine, sulfate reduction, and thermochemical sulfate reduction. The data from the various sites will help to assess the validity of the technique.

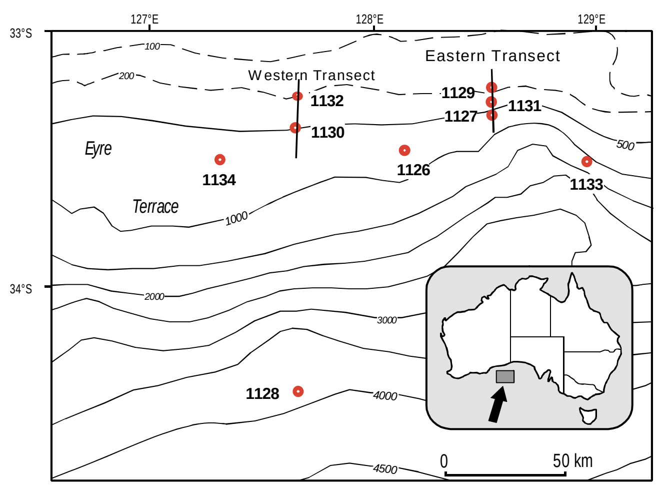


Figure 1. Location map of Site 1129, cored during Leg 182 of the ODP.

Project Description

The issue of carbonate associated sulfate (CAS), or sulfur trapped within the matrix of carbonate minerals, 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). In addition to obtaining the $\delta^{34}S$ of the

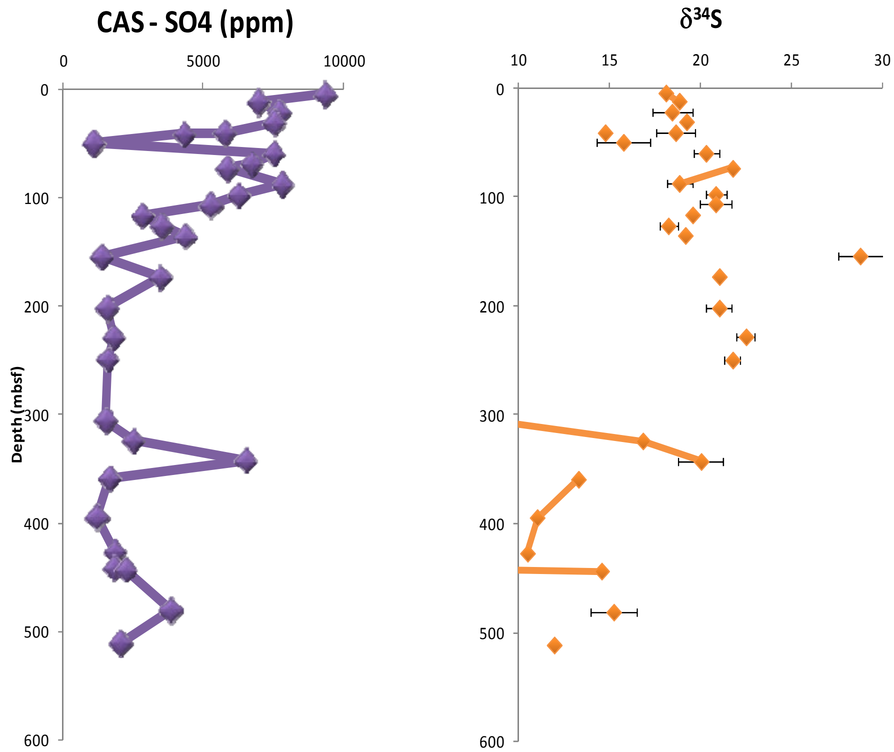


Figure 2. (A) The concentration of CAS as a function of depth. The decrease in the concentration of CAS reflects the loss of aragonite, probably not as a result of recrystallization, but rather as a change in the input of material. (B) Changes in the $\delta^{34}S$ of the CAS. Note that in the upper portion of the core there is a slight increase in the $\delta^{34}S$ probably reflecting the formation of dolomite in the presence of the current gradient in the $\delta^{34}S$ of the sulfate in the interstitial fluids. In the lower portion, the $\delta^{34}S$ are quite a bit lower probably indicating recrystallization at a time when the $\delta^{34}S$ profile was different than at present. The negative values suggest the oxidation of hydrogen sulfide.

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 sediments and the $\delta^{34}S$ would be slightly enriched as the process of sulfate reduction forms H_2S depleted in $\delta^{34}S$ thereby enriching the residual sulfate (Goldhaber and Kaplan, 1975). 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.

Preliminary results from the core at Site 1129 in the South Australian Bight show in the upper portion of the profile a slight increase in the $\delta^{34}S$ (Figure 2). This increase is much less than the increase in the $\delta^{34}S$ of the dissolved sulfate (data from Wortmann et al., unpublished), but the increase is consistent with the precipitation of about 5-10% dolomite. In the lower portion of the core, the $\delta^{34}S$ values of the bulk sediment are low (~10‰), suggesting the oxidation of isotopically light H_2S to sulfate and the subsequent incorporation into the carbonate mineral. As the present porewater profile does not display this pattern, this oxidation process must have occurred during an earlier period when the porewater profile was different than today. The data indicate that (i) the dolomite in the lower portion of the core is not forming at the present time, (ii) dolomite in the upper portion of the core is forming under the present geochemical regime, and (iii) at times in the past, oxidation of hydrogen sulfide has contributed to the sulfate pool.

Expected Results

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

References

Baker, P. and Kastner, M. 1981. Constraints on the formation of sedimentary dolomite. Science, v. 213: p. 214-216.

Burdett, J. 1990. Did major changes in the stable-isotope composition of Proterozoic sea water occur? Geology, v. 18: p. 227-230.

Dawans, J. and Swart, P.K. 1988. Textural and geochemical alternations in late Cenozoic Bahamian dolomites. Sedimentology, v. 35: p. 385-403.

Goldhaber, M.B. and Kaplan, I.R. 1975. Controls and consequences of sulfate reduction rates in recent marine sediments. Soil Science, v. 119: p. 42-55.

Katz, D.A., Buoniconti, M.R., Montanez, I.P., Swart, P.K., Eberli, G.P. and Smith, L.B. 2007. Timing and local perturbations to the carbon pool in the lower Mississippian Madison Limestone, Montana and Wyoming. Palaeogeography Palaeoclimatology Palaeoecology, v. 256: p. 231-253.

Katz, D.A., Eberli, G.P., Swart, P.K. and Smith, L.B. 2006. Tectonic-hydrothermal brecciation associated with calcite precipitation and permeability destruction in Mississippian carbonate reservoirs Montana and Wyoming. Aapg Bulletin, v. 90: p. 1803-1841.

Westphal, H., Eberli, G.P., Smith, L.B., Grammer, G.M. and Kislak, J. 2004. Reservoir characterization of the Mississippian Madison Formation, Wind River Basin, Wyoming. AAPG Bulletin, v. 88: p. 405-432.

Testing Carbon Capture and Storage using Stable Isotope Measurements of CO_2 in the Atmosphere

Peter K. Swart, Daniel Riemer, Tim Dixon, Falk Amelung and Guoging Lin

Project Purpose

Carbon sequestration is an important aspect of the response of the United States to the problem of anthropogenically induced global warming. The technology of sequestering CO_2 into underground reservoirs is known as Carbon Capture and Storage (CCS). However, assessment of the efficiency, safety, and long term fate of CO_2 sequestered into various types of geologic reservoirs remains a challenge. In this project we will deploy field instruments capable of measuring the stable isotopic composition of CO_2 in order to ascertain leakage from storage sites.

Scope of Work

Portable instruments capable of measuring the stable carbon isotopic composition of CO_2 (Cavity Ring Down Spectrometers; CRDS) will be deployed at sites where CO_2 is being actively pumped into underground storage reservoirs. These instruments will transmit their data through the internet to Miami and record a continual record of possible leakage from the reservoir. In addition background surveys will be made on a monthly basis to determine local variation in the $\delta^{13}C$ of local CO_2.

Key Deliverables

The geochemical work will be combined with geophysical data (GPS, Seismic, and In-SAR) to ascertain the effectiveness of CCS.

Project Description

During CCS liquefied CO_2 is pumped into underground reservoirs. The assumption is that the CO_2 will remain in the gaseous form and be trapped in the reservoir. However the possibility exists that the CO_2 will leak out of the reservoir and reach the surface. The escape of gas during sequestration will be monitored using a CRDS. This instrument can analyze both the concentration and $\delta^{13}C$ of CO_2. As fossil fuel-derived CO_2 has a characteristic carbon isotopic signature (-25 to -30 ‰) (Deines, 1980) relative to normal atmospheric CO_2 (-7 to -8 ‰), this technique can identify escaping fossil derived CO_2. While there are other processes which can also produce the negative carbon isotopic signature, such as respiration of organic material, large increases in the concentration of CO_2 in association with pronounced negative carbon isotopes over prolonged periods, would confirm escape of the sequestrated gas. In order to identify isotopic anomalies resulting from the escape of CO_2 it will be important to obtain information on the background levels and isotopic composition of CO_2.

The CRDS system uses the absorption of a laser signal coincident with the vibration frequency of the ^{13}C-^{12}C and ^{12}C-^{12}C bonds in the CO_2 molecule. Gas is injected into a cell and laser light is passed into the cell reflect off three mirrors. One of these mirrors allows a small amount of loss of light and the signal emitted from this mirror is monitored (ring down). The ring down or the loss of signal is proportional to the absorption of the laser signal by the ^{13}C-^{12}C bonds (Figure 1). Modern instruments are very robust and can attain precision approaching those measured using a standard stable isotope mass spectrometer. The plan will be to purchase two of these instruments (CRDS) and deploy one at the sequestration site in conjunction with GPS and seismic equipment. The CRDS instrument will continually monitor the $\delta^{13}C$ and concentration of the CO_2 at the site. On a monthly basis surveys over a 10 km x 10 km area will be made using a second instrument installed in a vehicle. This survey data will give us a 2-D picture of concentration and isotopic variation at the site.

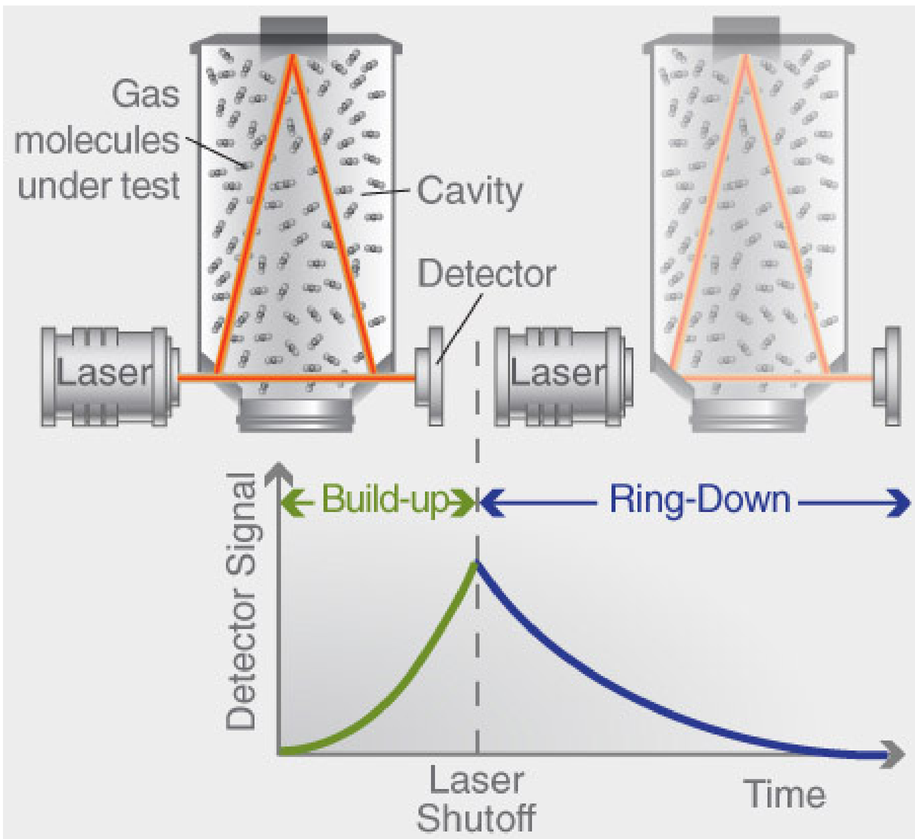
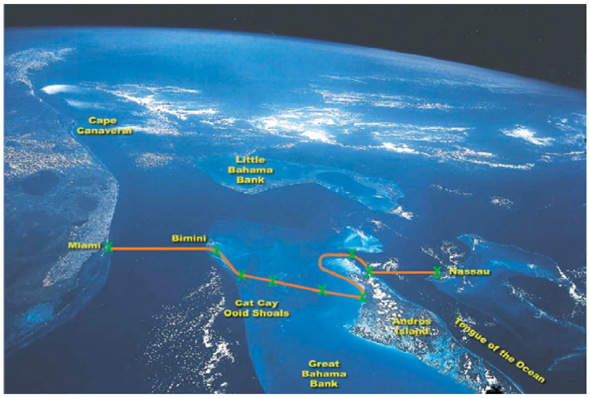
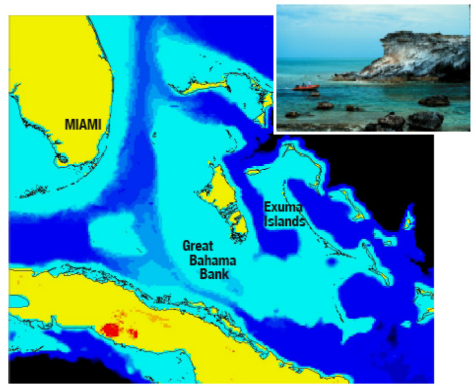


Figure 1. Schematic of a CRDS. The signal coming from the cavity is detected using a photo diode and is proportional to the concentration of the isotope absorbing the signal. The cell is 25 cm high, but the laser light bounces between the three mirrors giving an effective path of 25 km.

References

Deines, P. (Ed.) 1980, The isotopic composition of reduced organic carbon, 329-405 pp., Elsevier, Amsterdam.





Comparative Sedimentology Laboratory (CSL)
University of Miami
Summer Field Seminars 2010

The CSL invites the Industrial Associates to two field seminars in the Bahamas. The goal of these seminars is to acquire an exploration- and production-scale insight into carbonate platforms from modern analogs. To provide a comprehensive overview of the depositional environments we have organized two back to back field seminars:

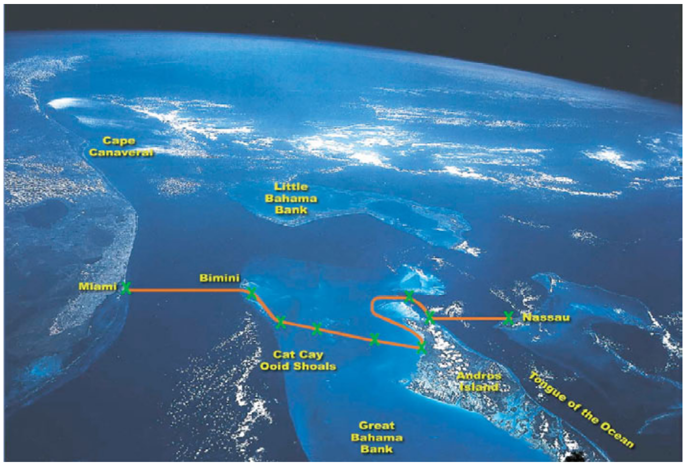
1. FACIES SUCCESSIONS ON GREAT BAHAMA BANK (June 21 – 26, 2010) is a field seminar combined with a seismic and core workshop. The field seminar is a platform transect from the leeward to the windward margin of Great Bahama Bank.

2. HETEROGENEITY OF BANK-MARGIN OOID SANDS (June 27 – July 2, 2010) focuses on the grainstone belt along the windward margin of Exuma Sound.

The days in the field are spent onboard RV/Coral Reef II, which has a capacity of 15 passengers. Each of the visited depositional environments will be discussed in regards to its importance in exploration and its heterogeneities in production. See attached flyers for details of both trips.

A participant attending both seminars will receive a 10% discount. Please RSVP by May 1, 2010 to kneher@rsmas.miami.edu or geberli@rsmas.miami.edu.

CSL
University of Miami



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1. Field Seminar

Offered by the Comparative Sedimentology Laboratory

FACIES SUCCESSIONS ON GREAT BAHAMA BANK

Implications for Exploration and Reservoir Characterization

June 21 – 26, 2010

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

Location: Begins and ends in Miami, Florida. The first day is a seismic and core workshop in Miami, followed by five days on a chartered boat that will cross Great Bahama Bank with stops at all important facies belts.

Objectives:

1. **illustrate the depositional processes and dimensions of facies belts** on an isolated platform.
2. **improve the interpretation of subsurface data** of carbonate systems
3. relate filling of **accommodation space and facies heterogeneities** to reservoir models.

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

Content: This seminar explores the vertical and lateral facies successions and heterogeneities of Great Bahama Bank. The seismic and core workshop on day 1 illustrates the architecture of the prograding western margin of Great Bahama

Bank. Cores across the platform margin provide a unique opportunity to examine the sequence stratigraphic distribution of facies and diagenetic modification in platform carbonate reservoirs. Log and laboratory data from these cores provide insights into porosity/velocity relationships and permeability distribution in platform carbonates.

As modern analogs, the facies belts on Great Bahama Bank display the depositional heterogeneities that may 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. Field stops include the leeward platform margin (Cat Cay Ooid Shoal), the platform interior, the tidal flats of Andros, the ooid shoals of Joulters Cay, patch reefs, and the Andros Island barrier reef. Pleistocene outcrops on Bahamian islands show how these facies are preserved in the ancient rock record.

For the complete program visit: http://www.cslmiami.info/learning/fieldSeminars

On the Cat Cay Ooid Shoal

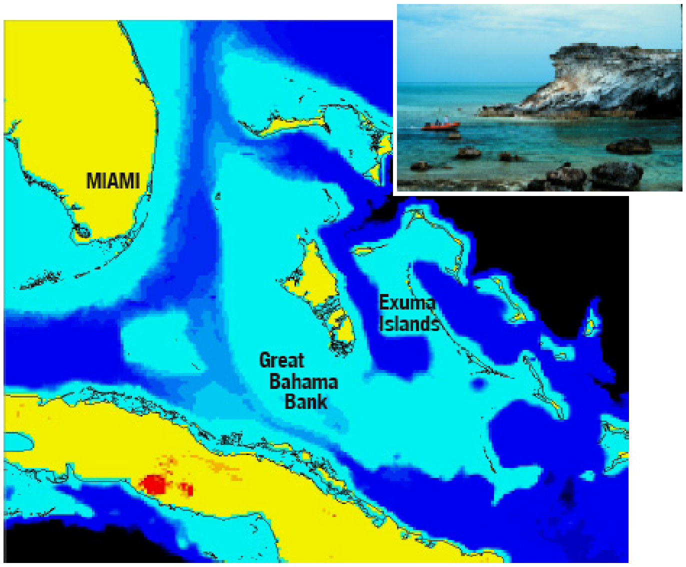
In an Andros Island tidal channel

Cost: $3,700.- Flights to and from the Bahamas, all ground transportation, on-board boat accommodation in the Bahamas, meals, and course notes are included.

Contacts: **Gregor P. Eberli** (305) 421 46 78 geberli@rsmas.miami.edu
Karen Neher (305) 421 46 84 kneher@rsmas.miami.edu

Registration: A soon as possible but no later than May 1, 2010 by contacting:

Karen Neher
Comparative Sedimentology Laboratory
4600 Rickenbacker Causeway, Miami, FL 33149, USA



2. Field Seminar

Comparative Sedimentology Laboratory

HETEROGENEITY OF BANK-MARGIN OOID SANDS

Depositional Models and Reservoir Analogs
Exumas, Bahamas

June 27 – July 2, 2010

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

Location: Exuma Islands, Bahamas where facies relationships and heterogeneity of a grainstone dominated, high-energy carbonate platform margin are exposed. We will visit by boat 14 different settings illustrating the various environments along the windward margin. Begins and ends in **Nassau, Bahamas**.

Objectives:

1) **illustrate the dimension of the large-scale exploration-scale facies belts** of a windward margin, and
2) **examine the smaller, reservoir-scale heterogeneity** within these grainstone facies.

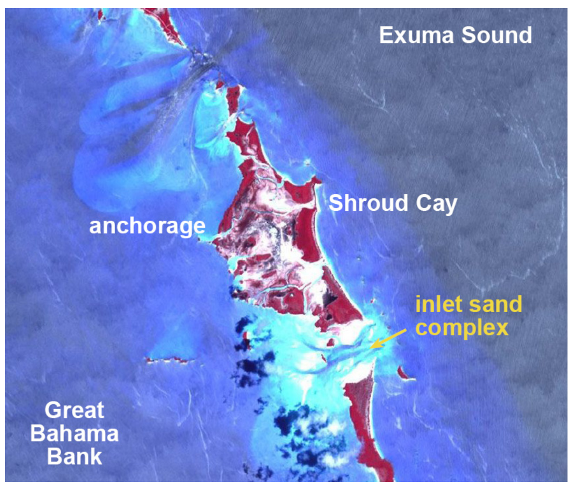
Who should attend: Exploration and production geoscientists and reservoir engineers working in (oolitic) grainstone reservoirs or on platform margin settings.

Seminar Content: The modern sediments combined with core material through the Pleistocene strata are used to illustrate the vertical-lateral juxtaposition of bank-margin lithofacies and the early diagenesis in these facies. The modern environment displays the sedimentary products that are produced by the physical and biological processes along the bank margin. 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. Corals and stromatolites in normal, open marine environments and tidal channels will demonstrate the reef building communities in these high-energy environments.

In short, the seminar will document the exploration-scale facies relationships and dimensions as well as reservoir-scale features in a high-energy platform margin including the spatial distribution of the sub-environments, disconformities, sub-aerial exposure horizons.

For the complete program visit: http://www.cslmiami.info/learning/fieldSeminars

In tidal channel of Shroud Cay



Shroud Cay ooid tidal complex

Costs: $3,500.-, Includes all ground transportation, boat, meals, and course notes with virtual field seminar CD.

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Gregor P. Eberli (305) 421 46 78 geberli@rsmas.miami.edu

Registration: A soon as possible but no later than May 1, 2010 by contacting:

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