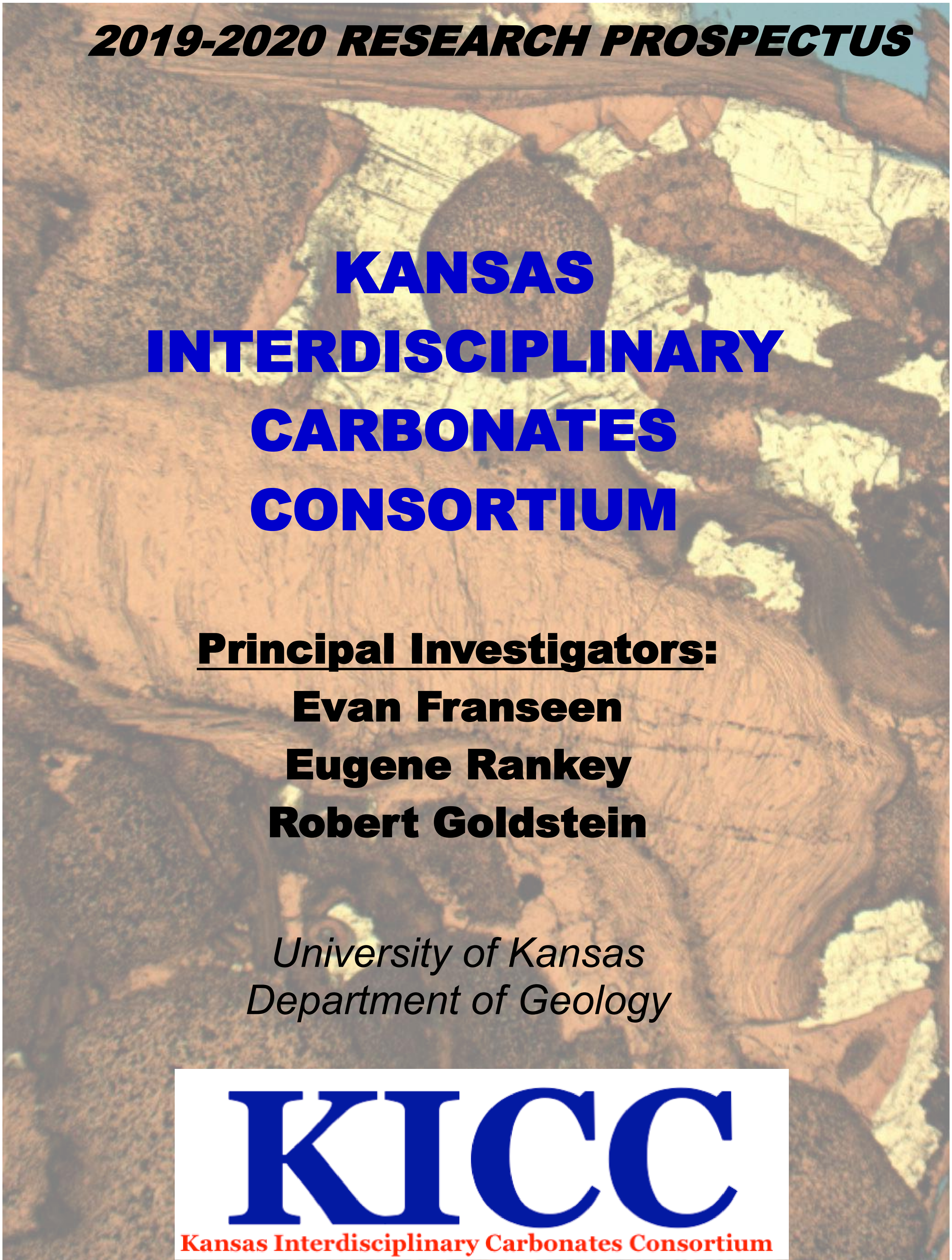

2019-2020 RESEARCH PROSPECTUS

KANSAS INTERDISCIPLINARY CARBONATES CONSORTIUM

Principal Investigators:

Evan Franseen

Eugene Rankey

Robert Goldstein

University of Kansas
Department of Geology

KICC

Kansas Interdisciplinary Carbonates Consortium

2019-2020 Research Prospectus

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KICC
Kansas Interdisciplinary Carbonates Consortium

An integrated program of research and training in carbonate systems

Principal Investigators:
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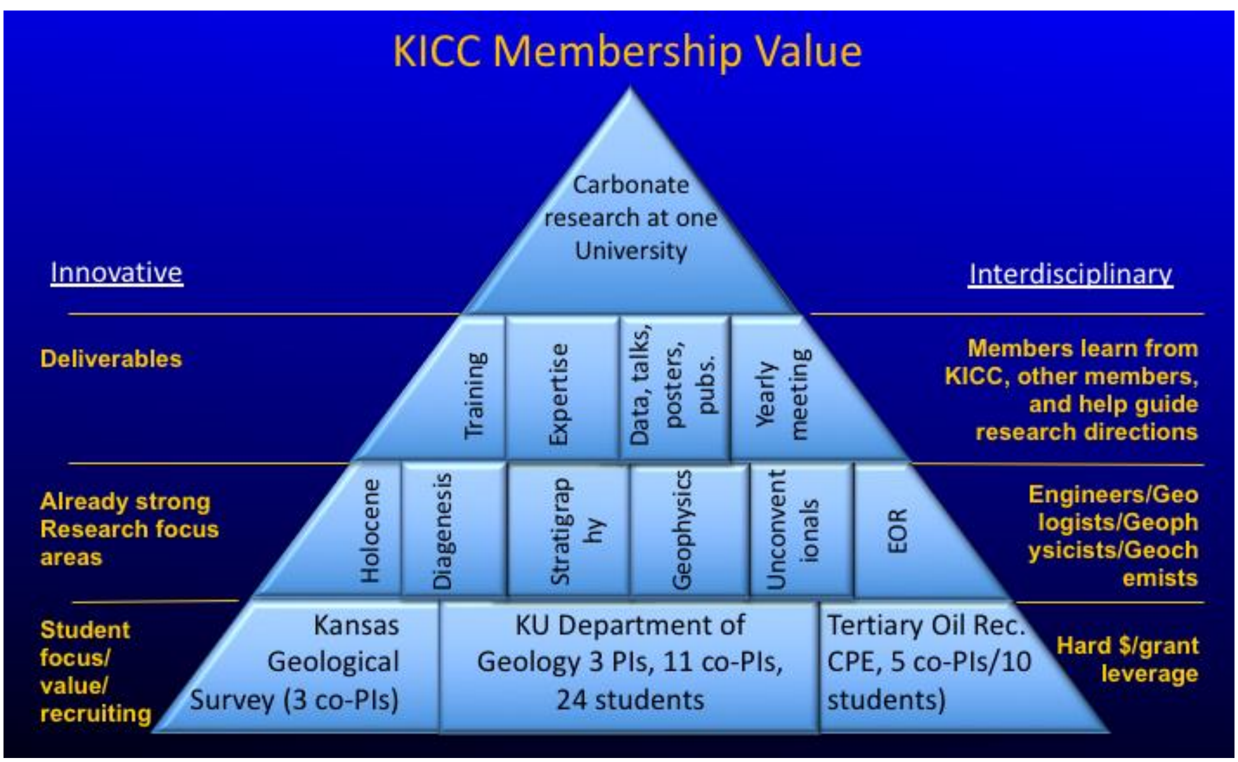
The KICC Program: Broad, Deep, Interdisciplinary

The Kansas Interdisciplinary Carbonates Consortium (KICC) is a research and training program specializing in carbonate sediments, rocks and reservoirs. The program is housed in the Department of Geology, Earth Energy and Environment Center at the University of Kansas, and benefits from interactions with the staff of the Tertiary Oil Recovery Program (TORP), Department of Chemical and Petroleum Engineering, and the Kansas Geological Survey (KGS). The program's focus is on fundamental and applied research on carbonates with industry relevance, including the following:

- Sequence stratigraphic controls on facies distribution in carbonates
- Carbonate diagenetic controls on porosity and permeability
- Geologic reservoir characterization, petrophysics and modeling
- Geophysical signatures of porosity, fractures, fluids, and facies in carbonates
- Carbonate-rich unconventional reservoirs
- Enhanced oil recovery/CO_2 sequestration
- Facies distribution and architecture of Holocene carbonates

Level of support

We request funding at a level of $45,000/year/company for full membership in the consortium and access to all deliverable products. All funds will be used for support of the KICC program. The University of Kansas Center for Research has agreed that no overhead will be charged.



KICC Projects Address Industry Challenges

The 2019-20 prospectus consists of 92 projects, which are presented individually after the introduction. Each project description starts with a "SUBSURFACE APPLICATION" header, which lists specific reservoir or oil and gas plays to which the study might be applied. Some applications are briefly listed here to highlight the diverse types of reservoir systems and spectrum of ages that KICC researchers study. Details found in each individual project highlight the wide range of approaches and disciplines used and integrated to examine these systems.

Subsurface application examples include:

- **Permian Basin Unconventionals** such as Avalon, Wolfcamp, Bone Spring, Leonard, Wolfbone
- **Low Resistivity Pay** such as STACK and Middle East reservoir systems
- **Mississippian Reservoirs** in the US Midcontinent including SCOOP and STACK
- **Hydrothermal Porosity Alteration** including Ghawar Field, North Field, Ladyfern, presalt Brazil/Angola, Mississippian Lincoln County Colorado, Tengiz, Trenton-Black-River, Arbuckle/Ellenberger, Pennsylvanian Permian Basin and Midcontinent, Mississippian Lime in Kansas and Oklahoma, Shale plays of the Permian Basin, and Bakken/Lower Lodgepole play
- **Deepwater** and slope carbonates in general including Tengiz and Korolev Fields in Kazakhstan, Miocene in southeast Asia, Avalon, Wolfcamp, Leonard, Bone Spring in Permian Basin, Cretaceous of Mexico
- **Niobrara**
- **Eagle Ford**
- **Organic Geochemistry and Porosity in Unconventionals** in general
- **Carboniferous Midcontinent Reservoirs**
- **Lacustrine Analogs** to presalt Brazil and offshore Angola
- **Microbial Reservoirs** such as Brazil, Angola, Smackover, Arbuckle
- **Heterozoan Carbonate Analogs** to offshore Venezuela and Offshore Vietnam
- **Sweet Spots in Unconventionals** based on diagenetic, sedimentologic and stratigraphic studies
- **Cretaceous Plays of Mexico**
- **Jurassic-Cretaceous** analogs to Middle East, offshore north Atlantic, offshore west Africa reservoirs
- **Permian Basin Conventional Reservoirs** such as Grayburg-San Andres, Canyon, Cisco, Strawn, Wolfcamp
- **Dolomitized Reservoirs** such as Smackover, Midcontinent Mississippian, Arbuckle, Grayburg/San Andres of Permian Basin, Mississippian Williston Basin, Arab
- **Unconformity-Related Porosity and Cementation** such as San Andres, Tengiz, Arbuckle/Ellenburger/Tarim, Pennsylvanian/Permian of Permian Basin and Midcontinent, Mississippian Midcontinent, Shuaiba, Lisburne Group of Alaska
- **Isolated Platform Reservoirs** such as Tengiz, Malampaya field, Philippines; Luconia province, Malaysia, Indonesia
- **Oolitic Reservoirs** such as Cretaceous and Jurassic of Texas, Mexico, Middle East, North Africa, Permian of Texas, New Mexico, Carboniferous of Midcontinent
- **Reefal Reservoirs** such as Cenozoic reservoirs in Southeast Asia, Iran, Iraq, Kenya, offshore west Africa, and the Gulf of Suez
- **Williston Basin Plays** such as Bakken-Lower Lodgepole
- **New Seismic Attribute advances**
- **New Petrophysical advances**
- **New Geochemical approaches**
- **Improved EOR techniques**

Defining Characteristics of the KICC

- **Industry relevance.** The faculty and staff's research and teaching cover a complete range of topics, closely aligned to industry-related interests. *Faculty have worked in or closely with industry for years, and are actively working on challenges facing industry.* See how each project relates to specific industry problems in the following summary.

- **Diversity and innovative nature.** The program is strongly interdisciplinary, including researchers in modern carbonate sedimentology, seismic imaging, ground penetrating radar, carbonate petrophysics, predictive carbonate diagenesis, quantitative sequence stratigraphy, reservoir modeling and fluid flow simulation, reservoir characterization, geochemistry, paleontology, ichnology and geobiology. The program is among the largest and most diverse of its type in North America. The strong *interdisciplinary approach is providing novel insight for better fundamental understanding of carbonate systems.* The program has grown in recent years to provide an impressively large and diverse group of students, faculty and researchers.

- **Collaborative basis.** The KU Department of Geology, Kansas Geological Survey, Department of Chemical and Petroleum Engineering, and Kansas Tertiary Oil Recovery Program (TORP) are known for collaboration; this tradition is evident in the KICC program. Most publications are jointly authored by students and multiple faculty or staff members with differing expertise. The program employs an interdisciplinary approach in which multiple faculty, with diverse backgrounds, commonly work together on research projects and student training. Geochemists, geophysicists, engineers, sedimentologists, and geobiologists all work together in teams to achieve common goals. Although this is not unique among carbonates programs, it is an integral part of the KICC culture, and results in research innovations. *KICC faculty know, and students learn, the value of teamwork.*

- **Student-centered approach.** The consortium is a fertile training ground for a large number of students heading to industry with carbonates expertise. Currently, the program has approximately 30 students completing research directly on or related to carbonates. *Students from KICC come from a solid community of scholars in which industry is appreciated.*

- **World-class facilities**. Part of being a leader in the field includes developing, utilizing, and applying advanced technology. The consortium includes *researchers and students intimately involved with state-of-the-art technology and advanced technology development*. The 140,000 ft^2 Earth Energy and Environment Center is a state-of-the-art facility focused on integration and outreach to industry partners. Instrumentation includes terrestrial LiDAR, fluid inclusion lab, raman microspectroscopy, stable isotope lab, diagenetic simulation lab, microbe lab, TIMS, laser probe high resolution-ICP-MS, ICP-MS, ICP-OES, U-Th/He lab, GC-MS biomarker lab, FIB-SEM with CL and BSE, NMR, SIP, 3D-visualization, micro-CT, advanced PVT, current meters, wave gauges, GPR, and high resolution seismic. Standard industry software packages are used for efficient student training and seamless transfer of results to industry supporters (e.g., Petra and Petraseis, Petrel, PerGeos, Dionysus, CMG-GEM, Eclipse, SMT-Kingdom Suite, Midland Valley Structural Modeling).

- **Systematic quantification**. A unifying theme of the KICC faculty is their focus on systematically, rigorously, quantitatively addressing controls on depositional process, sequence stratigraphic and diagenetic aspects of carbonates. *We go beyond "characterization" to rigorous, systematic, and quantitative approaches and prediction*. A central focus is on quantifying important variables, and feeding them into quantitative and conceptual predictive models. The team uses quantitative depositional process and diagenetic data to advance conceptual, forward, inverse, and cellular reservoir models.

- **Balance between fundamental and applied**. The approach involves a *balanced emphasis* on both fundamental concepts and practical applications. The fundamentals are proven by funding from agencies such as NSF, and productive students progressing to successful careers in academia, government, and industry research. The practical applications are proven by DOE, RPSEA, and industry funding, a large number of students going on to successful industry careers, and a long and continuing history of providing training for industry through leading short courses, symposia, field trips, and lectures.

- **Stepwise into the deep ancient**. As a program, KICC is able to take a stepwise approach into understanding ancient reservoirs. Its emphasis on the modern, informs its extensive research on the Miocene and Pliocene. Further research steps back into most time intervals of the deep ancient.

- **Engineers, geologists and geophysicists on the same page**. Each spring, students characterize a new relatively mature reservoir system for a company. Teams of geologists, geophysicists and engineers work as teams to characterize and model a reservoir, designing a waterflood or some other activity that is presented to the operator. Research projects show similar collaborations.

- **Enhanced oil recovery and CO_2 sequestration**. The program has extensive experience in carbonate systems with several DOE-funded projects.

- **Stability and value added**. KICC is staffed by investigators who are hard-money funded by the State of Kansas. The University of Kansas Center for Research has agreed to forego overhead charges on KICC membership contributions. Thus, membership funds can be spent directly on enhancing research.

KICC Primary Researchers

Principal Investigators:

- ***Evan Franseen*** – Professor and Senior Scientist, carbonate sedimentology, sequence stratigraphy, reservoir characterization
- ***Gene Rankey*** –Professor, carbonate sedimentology, stratigraphy, seismic attributes
- ***Robert Goldstein*** – Distinguished Professor, carbonate stratigraphy, diagenesis, fluid inclusions

Co-Principal Investigators (Department of Geology):
The Department of Geology educates undergraduate and graduate students in the fundamentals of theoretical and applied geological sciences so that they will have the knowledge and skills to adapt as the science and their personal and professional situations change. The Department houses approximately 100 undergraduate majors and 100 graduate students, and teaches geological sciences to approximately 4000 students each year. Its students and its 23 faculty conduct exemplary basic and applied research in the geological sciences resulting in more than 80 peer-reviewed publications each year. It produces the *Treatise on Invertebrate Paleontology* and contributes to the production of the *Journal of Sedimentary Research* and *Palaios*.

- ***Jennifer Roberts*** –Professor (Chairperson), Geobiology of carbonates, dolomitization, diagenesis, microbial CO_2 sequestration
- ***Luis González*** – Professor (on leave), carbonate geochemistry, diagenesis, stable isotopes
- ***George Tsoflias*** –Professor, Geophysics, ground penetrating radar, and high resolution seismic imaging of carbonates
- ***David Fowle*** –Professor, Geobiology of carbonates, microbial CO_2 sequestration
- ***Steve Hasiotis*** – Professor, trace fossils in carbonates
- ***Paul Enos*** – Emeritus Distinguished Professor, carbonate stratigraphy and diagenesis
- ***Alison Olcott***– Associate Professor, Organic geochemistry of carbonates and oil shales, microbial carbonates
- ***Craig Marshall*** – Associate Professor, geospectroscopy in carbonate systems
- ***Randy Stotler*** – Associate Professor, geochemistry and hydrogeology of carbonate systems
- ***Chi Zhang*** – Assistant Professor, geophysical monitoring sensitive to physicochemical properties, geophysical responses of geochemical and biological processes in the subsurface, rock/fluid interfacial properties, petrophysical models from geophysical datasets
- ***Hassan Eltom*** – Postdoctoral Fellow, Arab-D reservoirs; characterization of reservoirs; 3-D geostatistical modeling

Co-Principal Investigators (Tertiary Oil Recovery Program - TORP and Department of Chemical and Petroleum Engineering):
The Tertiary Oil Recovery Program was created to conduct research to explore tertiary methods to obtain additional oil from reservoirs. TORP's primary source of funding comes from the State of Kansas. Funding from the State is supplemented by funding from the U.S. Department of Energy (DOE) and industry. The DOE supplies funding for research contracts, technology

transfer to assist independent oil and gas operators and field demonstration projects to demonstrate how technology applications can improve oil and gas production. Industry funding comes in the form of fellowships and participation in field demonstration projects. TORP collaborates with oil and gas producers to submit proposals to DOE for field demonstration projects when requests for proposals (RFPs) are released by the DOE.

- ***Shahin Negahban* –** Associate Professor, carbonate EOR experimental and theoretical, DRP and rock characterization, PVT, geo-mechanics and fracture characterization, advanced EOR reservoir simulation
- ***Masoud Kalantari*** – Assistant Professor, numerical simulation and advanced data analytics techniques for conventional and unconventional resources
- ***Xiaoli (Laura) Li*** – Assistant Professor, CO_2 enhanced oil recovery and storage, phase behavior of solvents-reservoir fluid systems, multi-phase flow in porous media, shale gas reservoir development, anti-scaling and anti-waxing in oilfields
- ***Jyun-Syung Tsau*** - Associate Scientist, CO_2 Miscible Flooding, CO_2 Sequestration, Near Miscible Flooding, Phase behavior, CO_2-Foam Mobility Control, Fluid Flow in Porous Media, Numerical Simulation
- ***Reza Barati*** – Associate Professor, Hydraulic fracturing, unconventional, tight oil and gas, oilfield nanoparticles, CO_2 EOR-mobility and conformance control, enhanced water-flooding w/ modified injection brine

Co-Principal Investigators (Kansas Geological Survey):

The Kansas Geological Survey (KGS) conducts geological studies and research on the geology of Kansas and elsewhere. It specializes in emphasizing natural resources of economic value, water quality and quantity, and geologic hazards. The KGS has been providing research and service since 1889, and annually publishes extensively on subjects of economic interest. The Survey also produces computer programs and databases derived from geologic investigations. It has approximately 100 employees focused on research and service.

- ***John Doveton*** – Emeritus Senior Scientific Fellow, petrophysics
- ***Sahar Mohammadi*** – Assistant Scientist, carbonate diagenesis, petroleum geology, fault and fracture control on reservoir properties, Mississippian reservoirs, hydrothermal systems
- ***Franek Hasiuk* –** Associate Scientist, microporosity, geochemistry, petrophysical properties, 3D printing

Deliverables

1. An annual meeting of sponsors will be hosted each spring at the University of Kansas. This meeting will include talks by students and faculty on research progress. Importantly, the meetings will include ample opportunity for interaction among sponsors, faculty and students.

Each annual meeting will feature an optional short workshop, short course, or field trip on a subject of interest to carbonate geologists. Possible themes include:

- Grayburg/San Andres field seminar
- Sacramento Mountains field seminar
- hydrothermal alteration
- depositional environments of oolitic grainstones or isolated platforms
- build-and-fill stratigraphic architecture
- field trip on the Pennsylvanian in Kansas
- Mississippian workshop and field seminar
- Puerto Rico field seminar
- carbonate petrophysics
- quantification of variables controlling carbonate depositional systems
- the future of predictive studies in carbonate diagenesis
- stable isotope applications to carbonates
- fluid inclusion applications to carbonates
- geobiology applications to fine-grained carbonate oil-"shales"
- GPR & seismic applications to stratigraphic architecture and fracturing in carbonates

2. All publications, student theses, and digital versions of talks and papers will be made available to participants on the KICC website. Members will be alerted as publications are made available to participants well before public release in the literature. Digital versions of talks will be withheld from those who do not participate in the consortium. Each year, the sum total of products will be provided to members on DVD.

3. All participants will be acknowledged as supporters in publications and presentations.

4. Direct access to KICC experts who can serve as consultants to answer specific questions for individual companies, or otherwise interact with participants. Researchers will sign confidentiality agreements as necessary.

5. KICC experts will be available to sponsors for certain proprietary projects and more extensive projects of corporate interest with additional funding. Researchers will sign confidentiality agreements as necessary.

6. KICC will provide more advanced training for corporate participants on a fee basis. Training courses include a stable of short courses, workshops, and field seminars, offered as requested.

Research Focus and Examples of Projects

The KICC offers a portfolio of projects of broad interest to sponsors. Projects currently in progress or planned include the projects centered on the following themes:

- Geophysical signatures of porosity, fractures, fluids, and facies (11 projects)
- Carbonate diagenetic controls on porosity and permeability (16 projects)
- Facies distribution and architecture of Holocene carbonates (8 projects)
- Stratigraphic controls on facies distribution in carbonates (13 projects)
- Carbonate-rich unconventionals: Geobiology, sedimentology, geochemistry, exploitation of reservoir (13 projects)
- Reservoir petrophysics and reservoir modeling (19 projects)
- Enhanced oil recovery/CO_2 sequestration in dual porosity-dual permeability systems (12 projects)

In the following sections, each project is listed individually. The status of each project is listed in the STATUS line and presents if the project is seeking funding, if the project is complete and available to the KICC sponsors, and if the project is in progress with results available to the KICC sponsors. Among the 92 projects listed, 65 already have received partial or full funding previously from KICC or from other agencies. KICC sponsors benefit significantly from the value added by multiple funding agencies supporting the carbonates program at the University of Kansas. *All projects in this category will have results available to the KICC sponsors at or before the 2020 annual meeting (see listing below)*. The remaining 27 projects are presented as proposals to the KICC sponsors for recommendation for funding from KICC or other funds.

Summary of New Results Available:
Results from previously completed projects (not listed in this prospectus) are available to sponsors on the KICC website or upon request. Significant results from projects currently listed in this prospectus are also available and include the following 65 projects:

Stratigraphy/Sedimentology New Results Available

- Physical Oceanographic Influences on Miocene Carbonate Platforms of Central Luconia Province, Sarawak basin, Offshore Malaysia
- Birth, Growth, and Demise of Phanerozoic Isolated Carbonate Platforms
- Origin and Sedimentology of an Extensive Carbonate Breccia: Jelar Breccia, Croatia
- Shelf Break and Upper Slope Facies, Mid-Cretaceous, Mexico
- Origin of Paleosols in the Lofer Cycles, Alpine Triassic
- Sequence Stratigraphy and Reservoir-Analog Character of the Rellana Platform of SE Spain: An Analog to SE Asia Miocene Platforms
- Preliminary Analysis of Carbonate-Filled, Large-Diameter Structures in the Salt Wash Member of the Upper Jurassic Morrison Formation, Southeastern Utah: Implications for Correlating Significant Surfaces and for Fluid Flow

- Ichnological and Lithofacies Trends in the Spatial Variability of the Lower Permian Cedar Mesa Sandstone, Mexican Hat, Utah, Area: Dune and Interdune Environs to Gypsiferous Sabkha Deposits
- Ichnology and Paleopedology in Mixed Carbonate and Siliciclastic Environments: A Study of the Upper Pennsylvanian (Virgilian) Halgaito Formation, Southcentral Utah
- Sequence Stratigraphy and Reservoir Character of Miocene Tropical Heterozoan-Limited Photozoan Outcrop Analog Systems in the Caribbean
- Controls on Mississippian (Osagean) Inner Ramp Heterozoan Carbonate & Biosiliceous Deposits in a Midcontinent Setting
- Build-and-Fill Sequences in Carbonate-Dominated Systems: Towards Predictive Models for Reservoir Characterization

Diagenesis New Results Available

- Radiometric Dating of Carbonate Cements: Evaluating the Drivers of Fluid Flow and Porosity Evolution in Midcontinent Reservoirs
- Effects of Seepage-Reflux Diagenesis on Porosity Modification in Carbonate Reservoirs
- Superhighways for Hydrothermal Fluid Flow in the Midcontinent: Structural and Stratigraphic Controls on Thermal Structure, Flow Rate, and Reservoir Properties
- Quantifying Processes of Diagenetic Alteration in Mixing Zones: Cementation, Dissolution, and Dolomitization in Special Settings
- Modification of Reservoir Porosity by Hydrothermal Fluids: Recognition and Setting
- Experimental Approaches to Primary Low-Temperature Dolomite Formation in Carbonate and Mixed-Siliciclastic Systems
- The Role of Carboxylated Organic Matter in Low-Temperature Dolomite Precipitation
- Salinity Controls on Microbial Cell Wall Character and Impacts on Microbially Mediated Precipitation of Carbonates

Geophysics New Results Available

- Ground Penetrating Radar High-Resolution 3-D Imaging of Dual Porosity - Permeability Systems: Imaging Carbonate Lithofacies, Flow Units and Flow Conduits
- Imaging Fluid Flow and Transport in Discrete Fractures Using Ground Penetrating Radar
- Seismic Characterization of Carbonate Reservoirs in Kearney Co., West KS: Patterson & Hartland Fields
- Post-Stack Seismic Attribute Analysis and Impedance Inversion for Characterization of the Mississippian Reservoir, South-Central Kansas
- Porosity Prediction and Flow Unit Identification in the Mississippian and Arbuckle Reservoirs Using Seismic AVO Analysis and Pre-Stack Seismic Simultaneous Inversion

- Seismic Attribute Analysis of the Arbuckle Group from 3D-3C Data at Cutter Field, Southwest Kansas
- Seismic Anisotropy Investigation and Fracture Characterization in the Mississippian and Arbuckle Reservoirs, South-Central Kansas
- Seismic Stratigraphic Architecture and Geomorphology: Cenozoic Isolated Carbonate Platforms Systems
- Seismic Modeling of Geological Heterogeneity and Expression of Isolated Platforms
- 3-D Imaging of Facies and Porosity in Microbial Carbonates of the Messinian of Spain Using GPR

Holocene Carbonates New Results Available

- Investigating microbial and geochemical influences on microbialite formation
- Sediment Dynamics and Geomorphology of a Southeast Asia Isolated Platform: Holocene Layang-Layang Atoll, Malaysia, South China Sea
- Integrated Field and Modeling Analysis of Oceanographic Controls on Sedimentology of Holocene Ramp Carbonates: Yucatán Shelf, Mexico
- Redox-Sensitive Chemical Elements of Upwelling Ramp Systems: A Comparative Study of Modern and Ancient Carbonates
- Comparative Morphometrics of Facies Patterns of Carbonate Isolated Platforms and Rimmed Shelves: Holocene, Southeast Asia
- Controls on Sedimentation and Diagenesis in Modern Pre-Salt Analogues
- Comparative Ichnology of Holocene and Pleistocene Successions: The Role of Biota in Sediment Reworking

Reservoir Modeling/Characterization/Petrophysics New Results Available

- An Integrated Approach for Closed-Loop Microporosity Characterization
- Impact of Diagenesis on Reservoir Properties of Heterozoan Carbonates
- Grainy Heterozoan Carbonate Reservoir Models
- Effect of Bioturbation on Petrophysical Properties of Shelf Carbonates: Part 1: Lateral and Vertical Trends of Preferred Flow Pathways
- Effect of Bioturbation on Petrophysical Properties of Shelf Carbonates: Part 2: Geostatistical Modeling of Burrow Connectivity in 3D Framework
- Effect of Bioturbation on Petrophysical Properties of Shelf Carbonates: Part 3: Flow Simulation Modeling of Burrow Connectivity
- Comparative Ichnology of Pleistocene, Holocene, and Modern Carbonate Shoreface Deposits: A Predictive Ichnofacies Model and Effect on Rock Properties
- Flow Properties of Vuggy Carbonate Strata: Phase 1 - The Relationship between Vug Connectivity and Vug Fabric: Geostatistical Simulation to Understand Effective Flow in Vuggy Carbonate Reservoirs
- Flow Properties of Vuggy Carbonate Strata: Phase 2-Feasibility Study on Well Data and Flow Modeling to Produce Scenarios of Vuggy Porosity Connectivity and Effective Flow
- Digital Rock Physics of KICC Carbonate Formations

- Experimental Characterization of the Microporosity under Multiphase Flow Conditions Using a Micro-CT Scanner
- Petrophysics of Oolitic Grainstones and Their Evolution
- Integrated Geological and Petrophysical Expression of Oolitic Shoals
- The Oread Limestone: A Rosetta Stone for Carbonate Petrophysics and Seismic Stratigraphy

Unconventional Reservoirs New Results Available

- Diagenetic Controls on Distribution and Reservoir Character of Deep-Water Deposits in the Wolfcamp Plays of the Midland Basin
- Diagenetic Controls on Reservoir Character of the Wolfcamp and Bone Spring in the Delaware Basin, Texas
- Depositional Controls on Distribution and Reservoir Character of Deep-Water Deposits in the Permian Wolfcamp, Bone Spring, and Wolfbone Plays of the Permian Basin
- Application of Raman Spectroscopy to Determine Thermal Maturity in Different Windows of the Eagle Ford Shale and the Impact of Gas Huff-n-Puff
- Regional Microporosity Distribution in Kansas Cherty Carbonate Reservoirs (e.g., Mississippi Lime)
- Stratigraphic Controls on Reservoir Character of Chert-Rich Distal Ramp Strata: Mississippian (Osagean) South-Central Kansas
- Controls on Character of Chalky Low-Permeability Reservoir Analog: Miocene Agua Amarga Basin
- Diagenetic Controls on Porosity Evolution of Mississippian Strata in Well-Known and Emerging Plays in Oklahoma and Kansas
- Gas Transport in Shale Matrix Coupling Multilayer Adsorption and Pore Confinement Effect
- Ichnology of the Upper Cretaceous Greenhorn and Niobrara Formations of the Amoco Production Company Rebecca K Bounds #1 Well, Greeley County, KS

EOR, CO_2 Flooding/Sequestration New Results Available

- Seismic Imaging of CO2 EOR in the Mississippian Reservoir, South-Central Kansas
- Development of an Environmentally and Equipment Friendly Alternative for Matrix-Acidizing and Acid-Fracturing Applications
- An Integrated Workflow to Characterize Liquid Shale Candidates for Hydrocarbon Gas Huff-n-Puff
- CO2 Flooding to Improve Oil Recovery in Carbonate Reservoirs

Stratigraphic Controls on Facies Distribution in Carbonates

Carbonate sediments and stratigraphy reflect interactions among paleotopography, sea-level change, climate, productivity, and age. The research team concentrates on characterizing fundamental controls on 3D packages of carbonate strata by isolating variables in well-constrained systems. Examples of some current and pending projects include:

Three-Dimensional Heterogeneity in a Complex Ooid Grainstone: Integrated Stratigraphic and Geophysical Study of the Drum Limestone, Kansas

George Tsoflias, Evan Franseen, Gene Rankey, students

SUBSURFACE APPLICATION: Oolitic reservoirs (Cretaceous of Texas, Mexico, Middle East, North Africa; Permian of Texas, New Mexico; Carboniferous of Midcontinent U.S.A.)
STATUS: Proposed project
TIMING: To be completed in the future if recommended by membership
FUNDING: None

Purpose

The Drum Formation (Pennsylvanian, Missourian) in Kansas includes an oolitic body that is an analog to many producing hydrocarbon reservoirs. The characteristics of this limestone unit - its extension, geometry, volume and connection between different bodies, as well as its porosity and permeability - are closely related to depositional and diagenetic factors. The purpose of this project is to integrate detailed outcrop studies with high-resolution geophysical methods (LIDAR, reflection seismic, ground-penetrating radar - GPR) to image internal architectures and porosity distribution in three dimensions (3-D). The factors controlling porosity and permeability in the Drum Limestone may be applicable to other oolitic reservoirs in Kansas, the Midcontinent and other carbonate reservoir producing provinces.

Project Description

The Drum Limestone and associated strata crop out in SE Kansas, near the town of Independence in Montgomery County (Figure 1). The Drum Limestone forms a belt up to 40 km long and 30 km wide characterized by a high degree of variability in facies and thickness. It includes an oolitic body that changes laterally to the northeast (shelfward) to algal and bryozoan mounds (Feldman and Franseen, 1991). The thickness of the Drum Limestone varies from less than a meter to 24 m. It is wedge shaped and pinches out in both shelfward and basinward directions (Figure 2).

The skeletal oolitic grainstone facies (reservoir analog) is thickest and best exposed in the Heartland Cement quarry (site of this study; stratigraphic log shown in figure 2) where it is approximately 15 m thick. It consists of a range of facies from nearly pure, well-sorted oolite to poorly sorted oolitic fossiliferous grainstone and a small amount of packstone (Feldman et al., 1993). The main body of the oolite is well exposed in the mile-long (1.6 km) highwall of the Heartland Cement quarry and consists of thick (1-1.3 m) tabular, planar cross beds at the base that grade upwards to thinner, trough cross beds at the top (Feldman et al., 1993). Current orientations are predominantly to the southwest with a minor mode to the northeast (Hamblin, 1969). Troughs are separated by shale drapes that grade upward into isolated troughs surrounded by shale.

The Drum Limestone shows a distribution of cement and porosity closely related to sedimentary facies. The lower part of the oolitic body (oolitic grainstone) is characterized by early cementation and recrystalization of marine cements, high oomoldic porosity, and little compaction. The upper part of the oolitic body (skeletal oolitic grainstone) shows a higher percent of spar and dolomitic cements, less common moldic porosity and more compaction. Subtle subaerial features (e.g., autobrecciation, circumgranular cracking, root traces) are locally recorded in the oolitic body and linked to an intra-Drum subaerial exposure surface.

This project will integrate stratigraphic studies of the extensively exposed Drum Limestone at the Heartland Cement quarry with geophysical imaging for high-resolution, 3-D imaging of this reservoir analogue unit. Prior studies of the stratigraphic and depositional history of the Drum Limestone (Feldman and Franseen, 1991; Feldman et al., 1993) provide the basic geologic framework for this project. High-resolution geophysical imaging consisting of LIDAR, seismic and GPR will offer insights about the internal facies and geometry architecture and porosity distribution.

LIDAR scanning of the 1.6 km long, 15 m tall quarry wall will provide accurate and quantitative 2-D representation of facies thicknesses and internal geometries. High-resolution seismic and GPR will image multiple profiles parallel to the quarry wall which will be correlated to the LIDAR images and stratigraphy for generating 3-D reservoir analogue volumes of the Drum Limestone. Seismic and radar reflection volumes are expected to provide sub-meter scale imaging to a depth range of 0-10 m for GPR and 5-50 m for seismic. Seismic and radar signal attributes (e.g. interval velocity of propagation; interface reflectivity) will be correlated to lithology and porosity of the Drum Limestone in adjacent outcrops. If funded, cores behind the quarry wall will be taken to ground truth geophysical data away from the quarry exposure. Core plugs of all facies will be taken from the quarry wall and cores for porosity and permeability data.

Deliverables

This project will provide detailed 3-D reservoir-scale models of facies and porosity distribution of the Drum Limestone, which includes an oolitic body that is an analog to many producing hydrocarbon reservoirs in the Midcontinent and worldwide. Deliverables include integrated sedimentologic, petrographic, LIDAR, seismic and GPR data, as well as derived reservoir models in Petrel.

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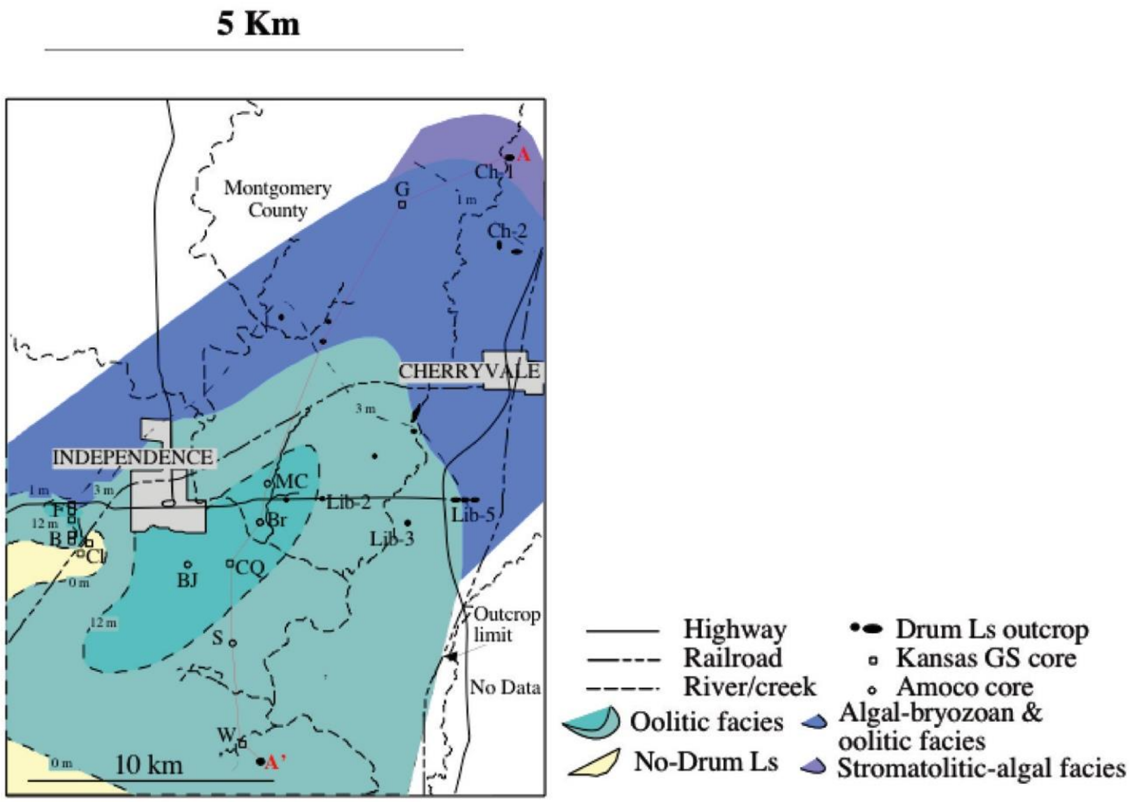

Figure 1. *Regional map of the Drum Limestone facies (Gomez-Perez et al., 1997).*

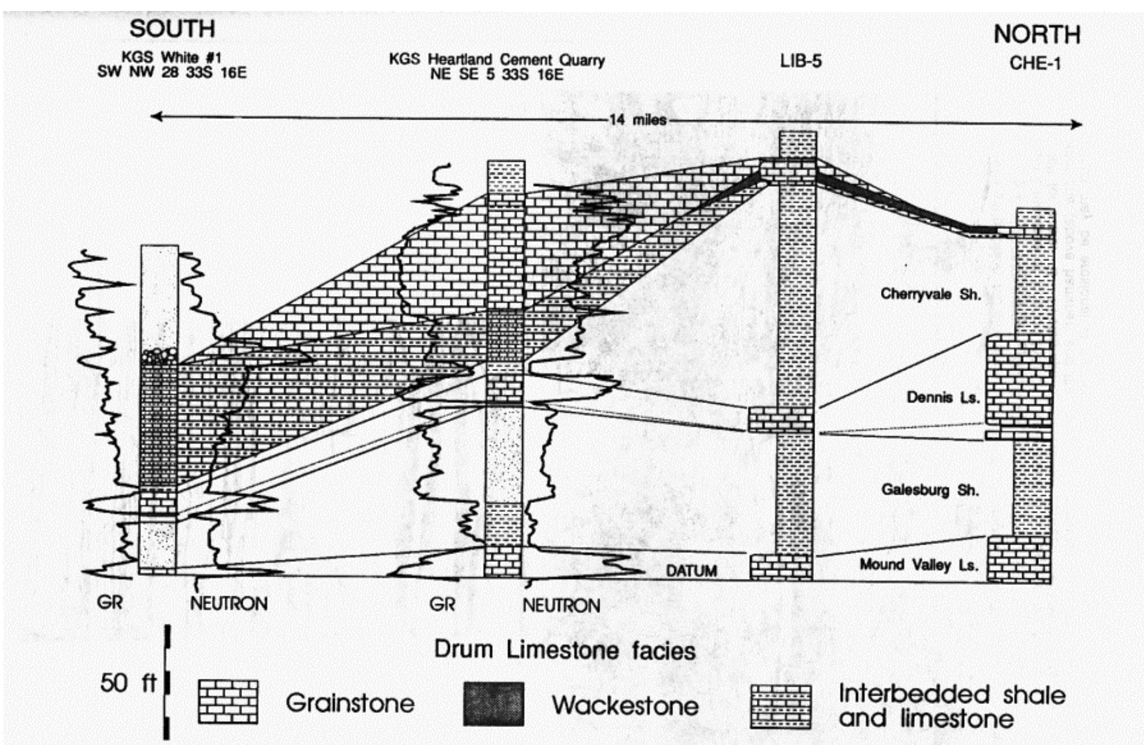

Figure 2. *Cross section of the Drum Limestone along the outcrop belt (Feldman and Franseen, 1991).*

Physical Oceanographic Influences on Miocene Carbonate Platforms of Central Luconia Province, Sarawak basin, Offshore Malaysia

Thomas Neal and Gene Rankey

SUBSURFACE APPLICATION: Many ancient isolated carbonate platforms contain prolific hydrocarbon reservoirs including the Silurian of the Michigan and Illinois basins, Devonian of western Canadian Basin, and the Carboniferous of Tengiz and other platforms of the former Soviet Union. The Miocene coral-algal reef reservoirs of the Central Luconia Province can provide insights into these ancient reservoirs and especially for other Cenozoic isolated carbonate platform reservoirs of southeast Asia.
STATUS: Part of a long-term project in progress
TIMING: Research starting summer 2019
FUNDING: KICC and AAPG

Purpose

Although the general controls on carbonate platform stratigraphic architecture are well known (e.g. sea-level change, tectonics, sediment supply), the nature and controls on their spatial variability and geomorphology are less well constrained. As part of a larger research effort analyzing Malaysia's Central Luconia Miocene carbonate platforms, this study takes the next step to examine the details of carbonate buildup architecture, facies, and controlling processes for a series of illustrative time slices within a stratigraphic framework. This project tests the hypothesis that ***changes in geomorphology and facies (their characteristics and distribution) are related to variable hydrodynamic forces within and among platforms across the shelf***. Overall, this study will enhance understanding of controls on the spatial variability of carbonate platform architecture and improve facies predictions of Central Luconia carbonate platform reservoirs, and carbonate platform systems in general.

Project Description

Located in the South China Sea, Malaysia's Central Luconia geological province is part of the Sarawak Basin off the northwestern coast of Borneo (Figure 1A). Many of the providence's 250 mapped Miocene carbonate buildups (Figure 1B) contain expansive gas (65 tcf recoverable) and some minor oil reserves (Koša et. al., 2015). During the Tertiary, the province was an area of extensive tropical shallow-water carbonate production and deposition within a tectonically complex region (Zampetti et al., 2004). Fluctuating sea level and tectonics influenced the growth and decline of these Miocene carbonate platforms (Epting, 1980). Seismic imaging reveals a variety of complex geomorphologies including aggrading, prograding, retrograding, and coalescing buildups with intercalcated platform-marginal carbonate and siliciclastic deposits (Zampetti et al., 2004; Bracco Gartner et al. 2004; Koša et. al., 2015).

To test the hypothesis and systematically explore the relationships among oceanographic forces, buildup geomorphology, and sedimentology, this project focuses on several specific objectives.

- First, map surfaces and seismic facies of two carbonate platforms across several middle Miocene time slices corresponding to distinct platform stages using seismic, core, and well log data, and interpretations from existing and ongoing studies.
- Second, build corresponding paleo-bathymetric maps and create numerical hydrodynamic models to estimate the waves, tides and currents across the shelf for these time slices. These regional models also provide a framework for higher-resolution numerical models for individual platforms.
- Third, use insights from our field and numerical hydrodynamic modeling study of Pulau Layang-Layang, an modern atoll analog just east of Luconia, to understand relations among location, bathymetry, oceanographic forces and sedimentology. Comparing predicted oceanography and paleogeography, and using oceanography-sedimentology relations, permit generating predictive facies maps for each platform, for several time slices or stages of platform growth.
- Fourth, test predictive facies maps against core data and independent predictions from seismic attributes (developed via separate, independent on-going project). Research will focus on the shallow platform tops (e.g. reef, reef sand apron and lagoon), as slope and margin areas have no available core data to test results. Although not a focus of this research, results will provide qualitative estimates on the direction and intensity sediment transport off the platform tops aiding in the prediction of slope to margin facies. The type of slope (accretional, bypass, or erosional) is important characteristic of carbonate platforms especially with predicting seals for potential reservoirs (Bracco Gartner et al., 2004).

Overall, the results are expected to provide details into the controls of buildup geomorphology, specifically the role of hydrodynamic forces on the variability of facies character and distribution in carbonate platforms. These data and models will provide general insights to the response of carbonate platforms to changing regional and global conditions in the Miocene, and carbonate platform systems in general..

Deliverables

This study explores the relationship between the oceanographic forces, carbonate platform geomorphologies, and the distribution and character of facies within these Miocene platforms. Expected results include process-based predictive models of facies distribution for various platform stages and how they change, and qualitative insights into relation between platform geomorphology and physical oceanographic parameters. Overall, this study will enhance understanding of the controls on the spatial variability of carbonate platform architecture and improve facies predictions of Central Luconia and other ancient platforms. This study supports the collective efforts of the larger project generating data and insights for conceptual models for heterogeneity in carbonate platform analogs (both modern and ancient) and examining broader changes and oceanographic controls on variability, with the goal to provide more accurate information to improve conceptual depositional models and heterogeneity for other ancient systems.

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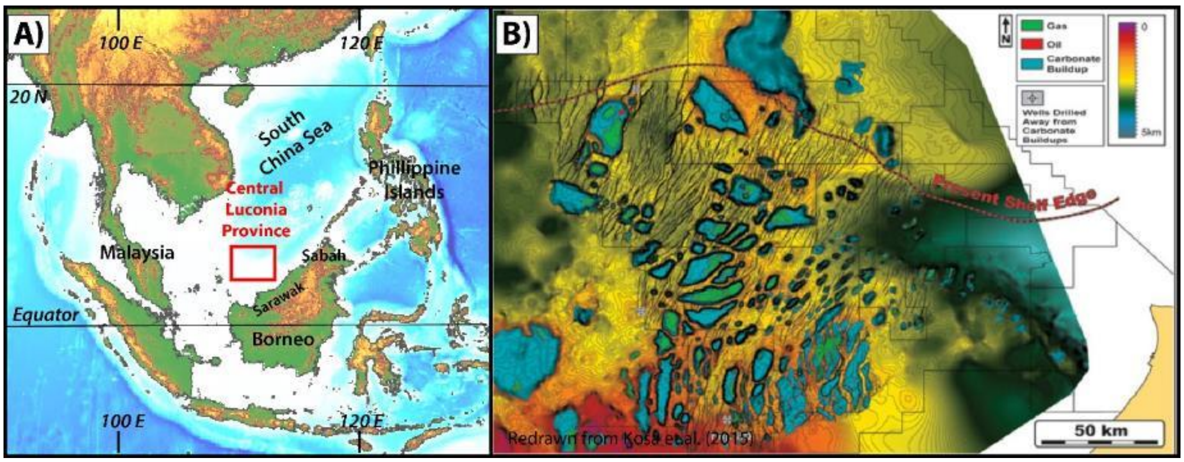

Figure 1. *Location of Central Luconia Province, Sarawak basin, offshore Malaysian Borneo A). Luconia's regional top carbonate map with gas and oil fields B). Blue indicates carbonate buildups. Green indicates known gas reservoirs and red are known oil reservoirs. From Kosa et. al. (2015).*

Birth, Growth, and Demise of Phanerozoic Isolated Carbonate Platforms

Gene Rankey

SUBSURFACE APPLICATION: Many ancient isolated carbonate platforms contain prolific hydrocarbon reservoirs, including: Silurian of the Michigan and Illinois basins, Devonian of western Canadian Basin, and the Carboniferous of the former Soviet Union, Miocene coralgal platforms of the Central Luconia Province, and other Cenozoic isolated carbonate platforms of Southeast Asia.
STATUS: Beginning a long-term project
TIMING: Research starting summer 2019
FUNDING: Seeking funding

Purpose

Since the Archean, thousands of isolated carbonate platforms have initiated, expanded, contracted, and, ultimately, terminated. These features are significant in that their stratigraphy includes important components of the Phanerozoic record of changes in sea level, paleoceanography, paleogeography, marine ecology and evolution; many also host important hydrocarbon reservoirs (e.g., Greenlee and Lehmann, 1993). They commonly also are markedly heterogeneous.

Although the biota, facies, stacking patterns, sequence stratigraphy, and diagenesis of numerous isolated carbonate platforms have been described and interpreted, trends in the genesis, evolution, and sizes among Phanerozoic examples remain poorly quantified – is every platform unique? If not, but instead there are themes, then they represent untapped predictive capacity and understanding (e.g., James, 1983; Wilkinson et al. 1985; Lehrmann and Goldhammer, 1999). Supplemented by the results of qualitative review of the literature, this study will analyze - systematically and quantitatively - a database of ***attributes in initiation, growth, character, and demise of more than 500 Phanerozoic isolated platforms***.

Research Objectives and Expected Results

To explore trends in Phanerozoic isolated carbonate platforms, this project includes several objectives:

Data Collection – Qualitative Trends: Students of isolated carbonate platforms have described, analyzed, and interpreted the genesis, growth, and termination of numerous examples from through the geological record. Documentation and explicit comparison of a few well-documented examples will illustrate some of the variety of these systems (e.g., Figure 1) and highlight some first-order trends.

Data Collection – Quantitative Trends: This project will review mostly published data, although some unpublished data are available to supplement the analyses. The focus will be on capturing a range of metrics related to the initiation, growth, architecture, and demise of isolated carbonate platforms. Metrics include both "processes" (presence of active tectonism, type of basinal sediment, tectonic setting, climate, etc.) and "product" (platform area, aspect ratio, thickness, vertical relief, stacking patterns, etc.). The database entries focus on examples with explicit description (e.g., nature and cause of platform termination) and/or specific quantitative data (e.g., area, aspect ratio, syndepositional relief, depositional gradient, thickness).

Analysis and Synthesis. In collecting a large number of examples, and then parsing the database systematically, trends or themes should emerge. Specific research questions range from:

- What proportion of isolated platforms are influenced by syndepositional tectonics? How are these controls reflected in platform size, aspect ratio, or other metrics?
- Are thicknesses and sizes of platforms consistent among geological eras? Are platforms of a Miocene age (for example) larger or smaller than platforms of other geological systems? Why, or why not?
- Are patterns of geometric evolution consistent through the Phanerozoic? Why, or why not?
- What factors influence platform termination? How do these controls change through time, related (for example) to icehouse-greenhouse global climate or geological age (e.g., biota)?

Both qualitative description and summary and quantitative analysis collectively will reveal the diverse origins, growth patterns, and termination of Phanerozoic isolated platforms. Although each platform is unique in many aspects, I expect the comparisons to reveal through-going trends and themes, patterns that represent predictive elements for enhanced understanding of heterogeneity in these iconic carbonate systems.

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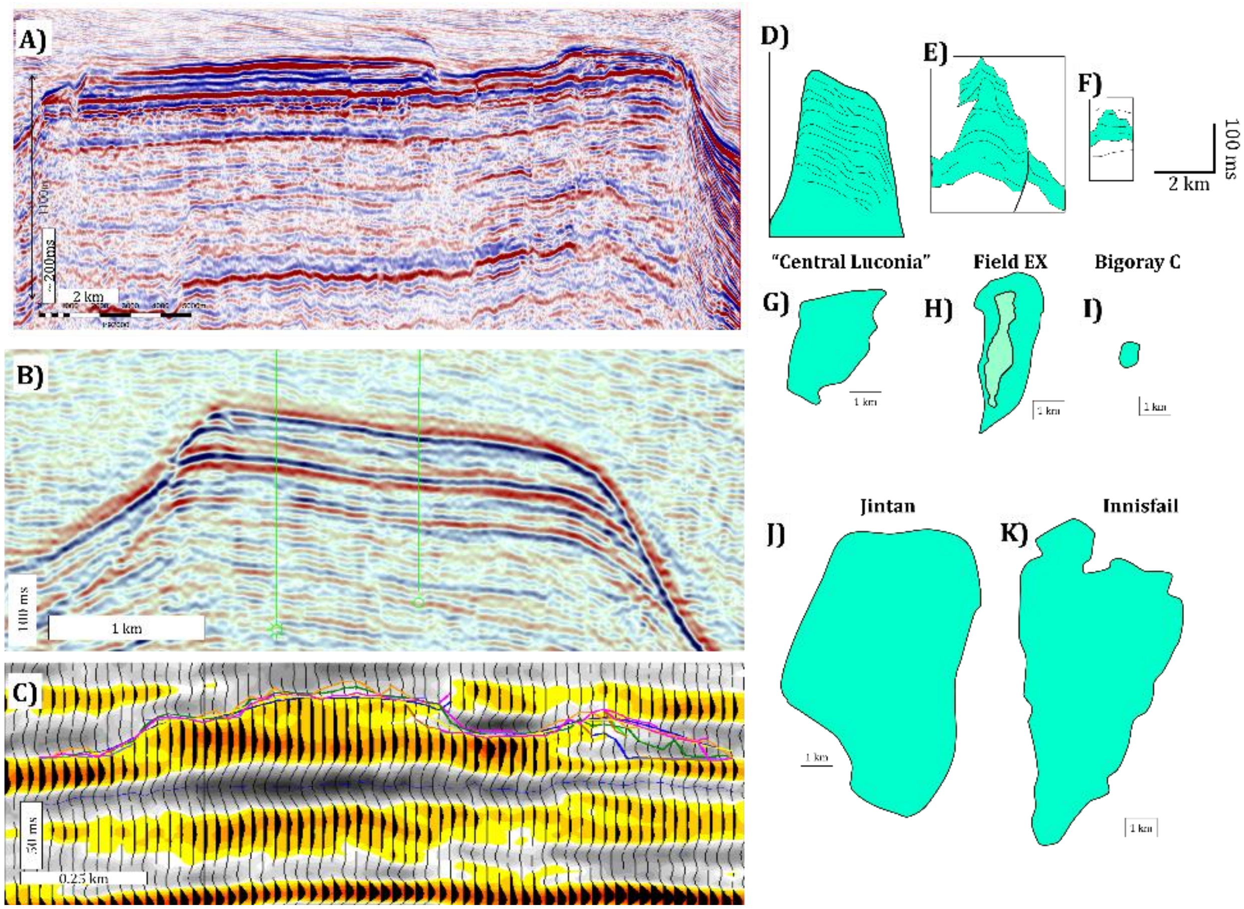

Figure 1. *Comparison of architecture and scale of illustrative Miocene and Devonian buildups. Note the spectrum in sizes of platforms. Yet, they include numerous common themes in evolution. A-C) Seismic lines, A – Jintan, Central Luconia, modified from Ting et al. (2011) [line is in depth, time is estimated using 3,750 m/s average velocity]; B – "Central Luconia Field," Masafarro et al. (2004); C – Bigoray C Field (Devonian), Rankey and Mitchell (2003).*
D-F) Sketches of seismic lines, plotted at same scale as Jintan (part A). D – "Central Luconia Field," Masafarro et al. (2004); E – Field EX, Ranket ey al. (2019). Plotted are Platform Stage 1 (medium blue) and Platform Stage 2 (light blue); F – Bigoray C Field, Rankey and Mitchell (2003).
G-K) Map-view outlines of buildups, all plotted on the same scale. G - "Central Luconia Field" Masafarro et al. (2004); H – Field EX, Rankey et al., (2019); I – Bigoray C Field, Rankey and Mitchell (2003). J- Jintan, Ting et al. (2011); K – Innisfail, Atchely et al. (2006). From Rankey et al. (2019).

Origin and Sedimentology of an Extensive Carbonate Breccia: Jelar Breccia, Croatia

Paul Enos and Igor Vlahovic

SUBSURFACE APPLICATION: Carbonate rocks of this age are prospective in the Adriatic basin. To our knowledge comparable breccia bodies have not been recognized in the subsurface.
STATUS: Long-term project in progress.
TIMING: Additional field work being scheduled with collaborators.
FUNDING: None at present. Past work supported by Croatian Geological Survey and KU discretionary funds.
STAFFING: Paul Enos, Igor Vlahovic (University of Zagreb)

Purpose

The origin of the widespread Jelar carbonate breccia is enigmatic, although most interpretations relate it generally to Dinaride tectonism. The sheer volume and local fabrics of the breccia suggest reservoir potential in the prospective Adriatic Basin. We know of no comparable deposits worldwide, but suspect that analogs may have been ignored as surficial deposits. Proper interpretation is important to understanding Dinaride tectonic evolution. An intended byproduct of this study is a systematic and manageable approach to field study of coarse-grained clastic deposits.

Project Description

The Jelar Breccia (Upper Eocene?-Lower Miocene?) covers fully 1% of the area of Croatia, although it is resticted to the main Dinaride fold-thrust belt. Outcrops are up to 10 km wide and 500 m thick (Vlahovic et al., 2007, 2011, 2012, 2018). Clasts are mostly Cretaceous through Eocene fragments of the Adriatic carbonate platform. Fine-grained crystalline carbonate fills most interclast pores, but angular clasts and grain support locally preserve appreciable porosity and some microporosity. Striking features of the breccia are the gradational nature and lack of clast rotation at the margins. Conventional wisdom is that Jelar breccia was debris from or disintegration of the front of major thrusts (Herak & Bahun, 1979; Tari & Mrinjek, 1994) but this is not consistent with regional distribution and structural details (Vlahovic et al., 2007, Vlahovic and Enos, field observations). It may, in fact, have led to misinterpretation of structures largely buried beneath the breccia. Some features are consistent with collapse breccia, although tectonics appear to play a dominant role in the origin.

Through detailed fieldwork coupled with regional distribution and structural paterns, we hope to elucidate the origin and evolution of this large body of rock. Although we can find no close analogs from the literature, it seems improbable that this prominent rock type is confined to one Alpine fold-thrust belt. (The similarity of the conventional interpretation to the original interpretations of the Cow Head Breccia of the Canadian Appalachians is striking, although modern interpretations of the Cow Head as submarine debris flows

(Hiscott and James, 1985) don't appear to fit the Jelar.) We suspect that analogous deposits have been neglected because of their complexity or dismissed as surficial deposits, e.g. talus or landslides.

In working out a plan of attack on the Jelar, we noted a lack of methodology for sedimentologic study of breccias. Thus our first goal is to develop a systematic and practical approach for gathering data. We have made significant progress in our exploratory field work, but we anticipate both refinements and innovations. The presence and distribution of microporosity within the breccia will be investigated using standard perm plugs and petrology.

Deliverables

a. Model for origin of carbonate breccia(s) in orogenic belts.
b. Maps of distribution of facies, grain size, particle shape, porosity, and permeability within the type example.
c. Methodology for sedimentologic study of carbonate breccias and other coarse clastic deposits.

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Shelf Break and Upper Slope Facies, Mid-Cretaceous, Mexico

Paul Enos

SUBSURFACE APPLICATION: Cretaceous shelf-margin and slope facies are the most prolific petroleum producers in Mexico's giant fields and are prospective around the Gulf of Mexico and the Atlantic margin.
STATUS: Project Proposed
TIMING: To be completed in the future if staffed and funded.
FUNDING: None at present. Potentially low-budget proposal.
STAFFING: Paul Enos, up to three MS students or one PhD

Purpose

The shelf break is a fundamental marker of carbonate platforms that can be readily recognized in outcrop and seismic records. Platform margin and slope deposits are major reservoirs of petroleum (cf. Roehl and Choquette, 1985) within carbonate deposits, which contain an estimated 60% of the world's oil reserves and 40% of natural gas (Schlumberger, 2007). A uniquely exposed mid-Cretaceous upper slope to shelf margin transition in the Sierra El Abra, Mexico, offers multiple opportunities to elucidate these key facies.

Project Description

Exposures of upper slope and transitional shelf-margin facies at Cementos Anahuac quarry, Sierra El Abra, Mexico, rival those of The Dolomites and the Capitan reef (J.L. Wilson, personal exclamation, 1994), albeit on a much smaller, more manageable, scale. Slope facies can be traced essentially up a paleoslope surface, from a reconstructed water depth of 270 m through the transition to shelf-margin rudist reefs and the immediate back-reef facies (Minero et al., 1983). The hypotheses that a) slope facies are very uniform over this depth range and b) grade rapidly and systematically into shelf margin facies with c) depth zonation from coral and rudist bioherms to marginal rudistid reef mounds (all based on preliminary observations) can be readily tested and documented for this example. Related research opportunities include: 1) Unraveling an extensive diagenetic history involving both meteoric and marine cementation (Enos, 1986, Minero, 1988, Wahab, 2017), which likely contributed to a stable slope angle of 43° (Enos. 1980, Minero et al. 1983, Wahab et al. 2015, 2016), 2) Seismic modeling of the reef-slope transition, using exposed geometry and rock properties, 3) Study of the myriad strike-parallel sedimentary dikes, an important aspect of early diagenesis and permeability evolution, and 4) An ancient analog to ongoing research by Eugene Rankey on modern upper-slope and shelf-margin facies of the Little Bahama Bank.

Methods will be largely conventional section measurement and petrology, from outcrop to SEM scale, using GIS techniques to reconstruct slope morphology and facies distribution. Seismic modeling will require measurement of density and acoustic parameters in large samples and application of standard seismic modeling programs. A detailed map of porosity distribution within the slope and transition facies will be a by-product of these measurements.

Deliverables

This project will produce sedimentologic and diagenetic facies analyses of a mid-Cretaceous upper slope to shelf margin transition with interpretations of effective processes. Comparisons with a modern Bahaman analog and available ancient examples (cf. Lehrmann et al., 1998; Emmerich et al., 2005; Minzoni, 2007; Minzoni et al., 2013) will guide generalizations from this example. Seismic modeling will greatly enhance the value of this study as an exploration model.

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Origin of Paleosols in the Lofer Cycles, Alpine Triassic

Paul Enos

SUBSURFACE APPLICATION: Paleosols, readily recognizable in cores and, with specific recognition criteria, in wireline logs, are among the most useful markers of sequence boundaries and sources of information on terrestrial environments during deposition. Soil material may fill extensive vuggy and moldic porosity developed during prior karstification of an underlying interval.
STATUS: Project Proposed
TIMING: To be completed in the future if staffed and funded.
FUNDING: None at present.

Purpose

Fossil soils (paleosols) provide records of past climates, delineate sequence boundaries, provide radiometric age dates for stratigraphic sequences, (Mack et al., 1993; Tabor and Myers, 2015) and may fill porosity formed in an underlying karst horizon (Enos and Samankassou, 1998), even to the extent of sealing faults (Cantarera et al., 2010). Research in the past several decades, based primarily in terrestrial sequences, has introduced quantitative proxies for changes in temperature, precipitation, and atmospheric *p*CO2 on local to global scales (Tabor and Myers, 2015, and references therein). Interpretations of paleosols in carbonate rocks have not kept pace (Wright, 1994; Azerêdo et al., 2015). Red conglomeratic to micritic carbonate intervals in the Dachstein Limestone of the Northern Calcareous Alps were related to soil formation as early as 1926, but details of their origin remain enigmatic. Field and laboratory study of these rocks should enhance interpretations and applications of similar lithologies and of carbonate paleosols in general.

Project Description

A persistent element within the famous 'Lofer cyclothems' of the Dachstein Limestone is discontinuous reddish, brown, yellow, green, or grey argillaceous lime conglomerate, breccia, or mudstone, which were interpreted as redeposited soil material in 1926 (Leuchs and Udluft, 1926; Leuchs, 1928). This interpretation was accepted and elaborated by (Fischer, 1964, p.123) and subsequent workers (Goldhamer et al., 1990; Satterley, 1996; Enos and Samankassou, 1998). Intimate association with supratidal deposits and paleokarst supports this interpretation. However, common features of carbonate paleosols, such as rhizoliths, pisoliths, laminated crusts, alveolar texture, clay cutans, negative $\delta^{13}C$ excursions, etc. (Esteban and Klappa, 1983; Wright, 1994) are notably scarce to completely absent, based on prior field and petrographic examination (Enos and Smankassou, 1998, 2007; Samankassou and Enos, 2019). Given their major role in defining cycles and cyclostratigaphy (Samankassou and Enos, 2019, and references therein) these paleosols warrant more detailed study and interpretation. Initial field examination, petrographic study, including electron microscopy (Kuznetsova and Khokhlova, 2012), and geochemical analyses will focus on conditions attending soil formation and the significance of the kaleidoscope colors. It is problematic whether more sophisticated quantitative paleoclimate interpretations will be possible, but data obtained may help advance this endeavor in carbonate paleosols.

Deliverables

Measured sections highlighting the occurrence of paloesols in the Dachstein, analysis of the role of paleosols in defining sequence boundaries, interpretation of the environmental conditions in the Tethyan Late Triassic, suggestions for applications to other platform carbonate sequences, and suggestions for advancing research on carbonate paleosols.

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Sequence Stratigraphy and Reservoir-Analog Character of the Rellana Platform of SE Spain: An Analog to SE Asia Miocene Platforms

Robert Goldstein, Evan Franseen, Rafferty Sweeney

SUBSURFACE APPLICATION: Middle East, including Cretaceous and Tertiary carbonates from the Gulf (Iran, Iraq, U.A.E., Qatar, Oman), reefal platform reservoirs from SE Asia, including Indonesia, and offshore Vietnam, offshore Venezuela
STATUS: Focused-term project now complete
TIMING: Complete
FUNDING: Partial from University of Kansas

Purpose

The purpose of this project is to study a superbly exposed cross section of the Rellana platform (Figure 1) to establish a detailed sequence stratigraphy and sea-level history, evaluate the influence of paleotopographic variations on platform facies and geometries, establish the process-response model for platform facies by incorporating data from neighboring basins, and complete a full basin-to-platform sequence stratigraphic interpretation for the Agua Amarga basin.

Project Description

The Rellana platform is an excellent analog for subsurface Miocene carbonate platforms, including major hydrocarbon targets in Southeast Asia. The development of a basin-to-platform sequence stratigraphic framework and understanding of controls on sedimentary patterns, will allow for a more complete prediction of heterogeneity in these reservoirs and facilitate prediction of platform-to-basin geometries in the subsurface. *In particular, this study will test the effects of substrate topography on rates of progradation and backstepping of reef facies.*

In addition, it is clear that there is a link between shelf processes and prospective basinal carbonate facies in the adjacent Agua Amarga basin (Figure 2). *Developing a conceptual link between observations on the shelf and facies in the basin will allow already discovered shallow water Miocene reservoirs to be used to predict the location and character of deepwater reservoirs in adjacent basins.*

The area of study for the project is a coastal exposure that provides one of the most laterally extensive 2-D cross sections through the entire platform, essentially perpendicular to the platform margin. Yet compared to adjacent areas, the Rellana platform remains unstudied. Reconnaissance study indicates the platform, which developed and prograded on relatively gentle Neogene volcanic basement paleotopography, is undeformed and consists of basal heterozoan facies, overlying photozoan reef and forereef facies, and oolitic, thrombolitic, stromatolitic, coral reef facies that form the top sequence of the platform.

Field work will include measurement of approximately twenty stratigraphic sections, including measurements with a hand-held spectral gamma ray logging tool. Sequences, facies, contacts, fractures and faults will be physically traced utilizing photo mosaics to assist in the identification of stratigraphic relationships. Tracing will extend into the adjacent Ricardillo area and the Agua Amarga basin margin area to tie into sequences and facies already documented in those areas. Approximately five hundred hand samples will be collected from major facies for petrographic study.

Deliverables

The sequence stratigraphy of the Rellana platform area is expected to contain five sequences (e.g. Toomey, 2003; Dvoretsky, 2009; Figure 2), ranging from lower heterozoan carbonate sequences upwards into photozoan carbonates, which include corals. The uppermost sequences are composed of ooid grainstone, thrombolites, stromatolites, and local coral reefs (Toomey, 2003).

The examination of the sequence stratigraphy and facies distribution on the Rellana carbonate platform will complete the development of a platform-to-basin model, which can be used to enhance predictive models for reservoir characterization, enhance our understanding of how substrate morphology interacting with sea-level controls reef progradation and backstepping, and will aid in development of platform-to-basin process-response models.

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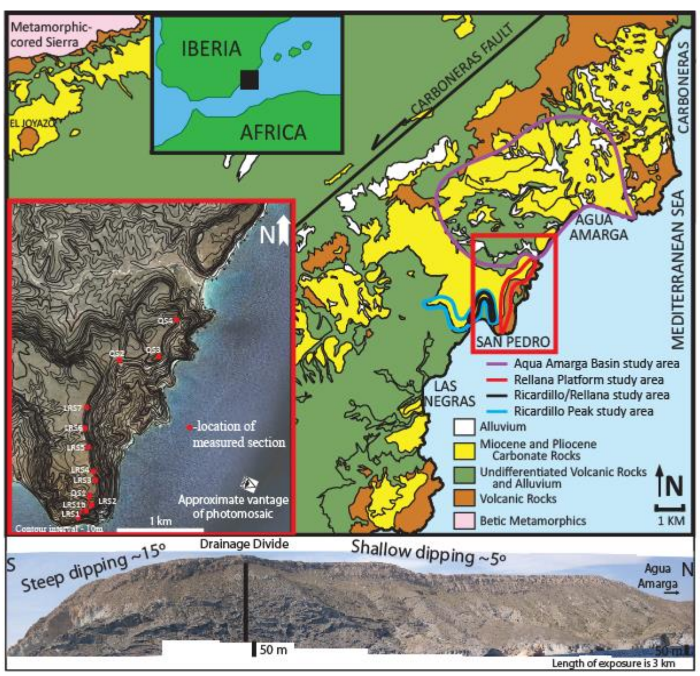

Figure 1. *Location and general geological map of the Cabo de Gata region of southeastern Spain. The Rellana study area is indicated by the red polygon. Previously described areas immedately adjacent to the Rellana platform include Ricardillo peak (blue polygon; Toomey, 2003), Rellana/Ricardillo area (black polygon; Lipinski, 2010) and the Agua Amarga Basin (purple polygon; Dvoretsky, 2009). Map Modified from: Mapa Geológico de España, 1981; Dvoretsky, 2009; Lipinski, 2010. Red rectangle inset and corresponding map shows topographic map (10 m contour interval) overlain on satellite image of Rellana Platform area with location of measured sections.*

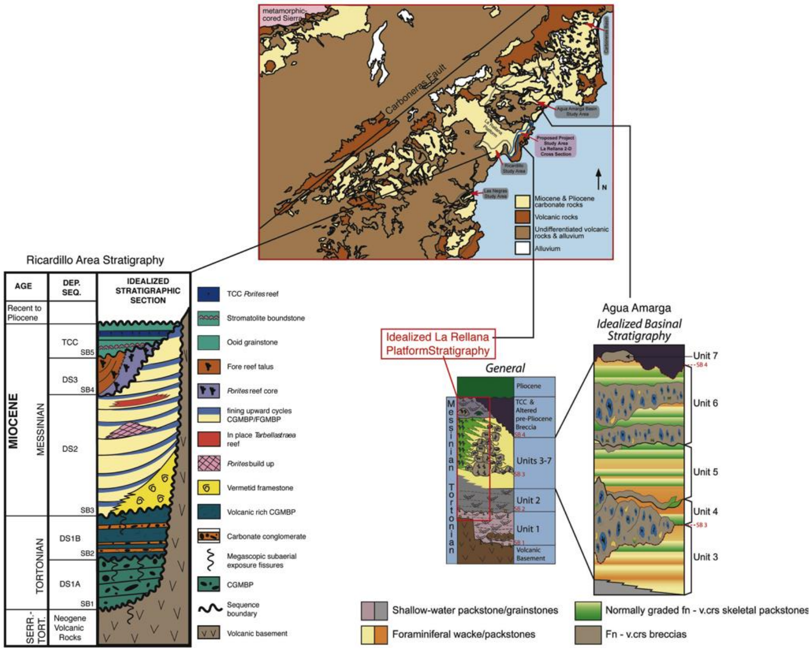

***Figure 2**. Results from previous studies in the Ricardillo area and the Agua Amarga Basin area; the La Rellana platform is situated between these areas. Through comparison of time-equivalent sequences and preliminary observations, it is possible to generate a generalized stratigraphy for the study area.*

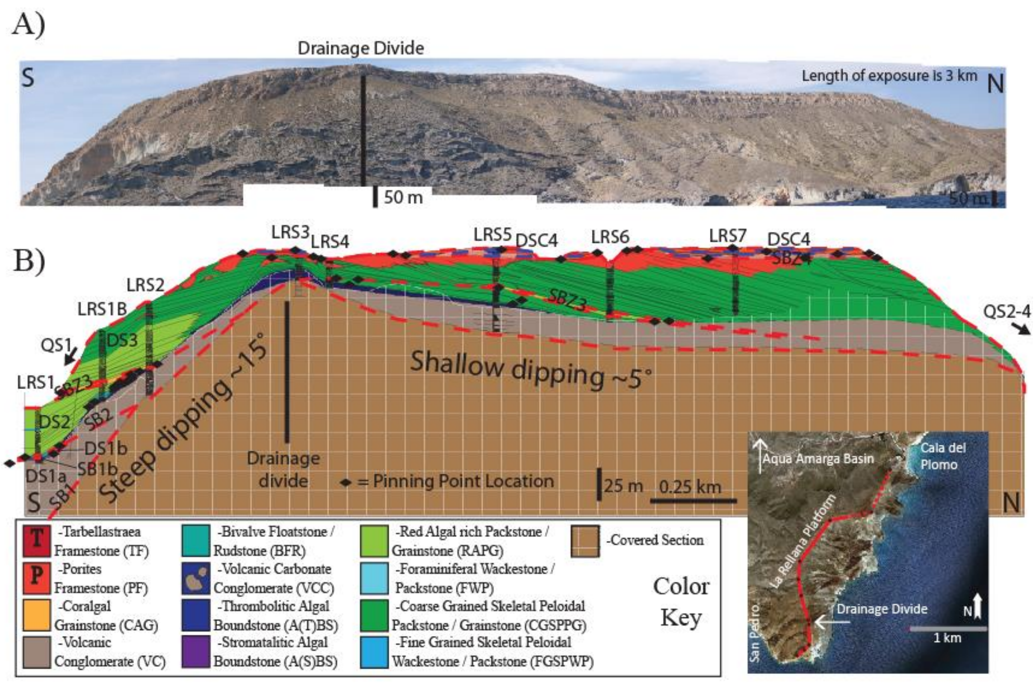

***Figure 3.** Exposure of the Rellana platform. A) Photomosaic of the southeast-facing Rellana platform. Carbonate reef-rich deposits generally resistant cliffs on the top of mostly covered volcanic deposits. B) Cross section through the Rellana Platform. Vertical exaggeration of cross section is 1.5 X.*

Preliminary Analysis of Carbonate-Filled, Large-Diameter Structures in the Salt Wash Member of the Upper Jurassic Morrison Formation, Southeastern Utah: Implications for Correlating Significant Surfaces and for Fluid Flow

Stephen T. Hasiotis and a student

SUBSURFACE APPLICATION: Reservoir rocks and their time equivalents in the oil and gas fields in the basins of the fold and thrust belts in the Rocky Mountains region
STATUS: Phase 1 of this project; expanding on previous work.
TIMING: 2 (MS student)–4 (PhD student) years
FUNDING: Seeking funding from sponsors

Purpose

Sediment texture can be modified by the activity of organisms after deposition; these processes can either degrade or enhance porosity and permeability. Systematic descriptions and assessment of the possible impact on reservoir quality and connectivity are few (e.g., Cunningham et al. 2009). Large-diameter, carbonate-filled burrows, in the Salt Wash Member (SWM) of the Morrison Formation that represent vertebrate burrows are found in sandstone, siltstones, mudstones, and mudrocks interbedded within relatively thick, laterally continuous sandstones. ***The purpose of phase 1 of this study is to (1) evaluate the effect of such large diameter burrows in continental deposits as macropores and macrochannels that can affect reservoir interconnectivity and the integrity of seal characteristics as barriers or baffles; and (2) determine the sequence stratigraphic significance of such burrow-bearing surfaces that can be traced over long distances in outcrop.***

Project Description

Carbonate filled, large-diameter burrows (LDB) can be traced in outcrop for over 2 km and represent a series of significant surfaces. Difference in lithologies between LDB fill and matrix will have an effect on the movement of groundwater and hydrocarbons. LDB may act as macrochannels, and their effect will be dependent on their density and distribution. Density is estimated to be 9 LS/10 m2, though their distribution is not uniform across the outcrop. LDB macrochannels can increase permeability, preventing the mudrock matrix from acting as a barrier to fluid flow and improving connectivity between underlying and overlying sandstones. Applying spatial ichnologic and sedimentologic data from this and previous studies of the SWM near the study area can greatly improve our understanding of how terrestrial bioturbation affects reservoirs and seals.

LDB in the SWM of the Upper Jurassic Morrison Formation near Ticaboo, Utah (UT), represent vertebrate burrows. The SWM is composed of interbedded sandstone, siltstone, mudstone, and mudrock that represent fluvial systems. The depositional environment of the LDB-bearing units represents a proximal to distal floodplain. LDB are located in the third paleosol down from the top of the SWM. Sandstones with pebble conglomerate lenses representing crevasse-splay events are interbedded with the LDB-bearing paleosol and other paleosols. The paleosols contain many slickensides. A second locality with similar lithologies is east of Capitol Reef National Park near Torrey, UT, where paleosols are thinner and the LDB are smaller in diameter and length.

LDB have two morphotypes. Morphotype 1 (M1) is most common and composed of a vertical to subvertical helical shaft that leads to one or more horizontal tunnels. Longitudinal and transverse striations are visible on the top of M1 specimens but are poorly preserved due to carbonate cementation. Side and bottom surfaces lack striations and are coated with smooth bumps of carbonate. Morphotype 2 (M2) is composed of a subhorizontal tunnel, with fewer longitudinal and transverse striations preserved than on M1. Striations are also distorted, and the major surface texture is bumpy. All LDB underwent significant architectural deformation due to the carbonate cementation. The complex architecture of M1 resembles mammal and therapsid burrows; the architecture of M2 resembles reptile burrows. The longitudinal and transverse striations on all LDB are interpreted as claw marks or bite marks.

To characterize the distribution of LDB and their effects as macrochannels and macropores in lithologies typical of seals in between typical reservoir units, multiple sections will be measured to capture lateral variations in continental environments, fine-grained lithofacies, and LDB morphology, depth, and connectedness to overlying and underlying sand bodies. LDB-bearing units will be traced laterally to determine how the extensiveness of their distribution. Two units to date have been traced over 2 km and 5 km. At each section, the general sedimentologic, ichnologic, and paleoecologic aspects will be described, including the type, size, and depth of traces. Burrows will be studied for their morphology and tortuosity in order to understand the number and depth of branching and, by proxy, the form and shape of macrochannels. Sediment from burrow fills will be compared to the surrounding matrix to determine how burrow fills affect local porosity and permeability. Thin sections will be made of the burrow and matrix to determine internal and external porosity and permeability. These morphologies and burrow fills will be used also to determine if flow might occur between the outside burrow wall and matrix—serving as an annulus through which fluids can migrate. All of these data on bioturbation patterns—field and lab analyses—in phase 1 will be tied together to determine if and how these burrows can act as barrier or baffle breakers when they occur with mudrock and mudstone, and if they serve a marker of a stratigraphically significant surface in continental settings.

Deliverables

LDB may be important as macrochannels and macropores for: 1) increasing the interconnectivity of reservoir bodies; and 2) serving as Kv and Kh pathways through fine-grained lithofacies typical of baffles or barriers to fluid flow. This research will provide 1) a photocatalog of trace fossils and lithofacies associations, and 2) the sequence stratigraphic significance of such LDB-bearing paleosols of weak to strong development over local to regional context.

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Figure 1*. Multiple examples of Morphotype 1 LS in place.*

Figure 2*. Detail of Morphotype 1 LS showing major architectural elements.*

Ichnological and Lithofacies Trends in the Spatial Variability of the Lower Permian Cedar Mesa Sandstone, Mexican Hat, Utah, Area: Dune and Interdune Environs to Gypsiferous Sabkha Deposits

Stephen T. Hasiotis and a student

SUBSURFACE APPLICATION: Reservoir rocks and their time equivalents in the oil and gas fields in the basins of the fold and thrust belts in the Rocky Mountains region
STATUS: Phase 1 of this project; expanding on previous work.
TIMING: 2 (MS student)–4 (PhD student) years
FUNDING: Seeking funding from sponsors

Purpose

Large-diameter burrows (LDB) within the Lower Permian Cedar Mesa Sandstone (CMS) represent vertebrate burrows of probable amphibian or reptilian origin. The LDB create macrochannels and macropores within the continental siliciclastic, carbonate cemented siliciclastic, and evaporitic deposits, modifying the original effective porosity and horizontal and vertical permeability of the strata. In the up-dip area, fine-grained, carbonate-dominated paleosols bound eolian-dominated sedimentary packages as well as eolian interdune and interbedded fluvial deposits. In the down-dip area, fine-grained, gypsum-dominated lithofacies of eolian, alluvial plain, and paleosol settings. Paleosols and trace fossils indicate wetter conditions that overprint eolian processes that can produce barriers to flow; traces themselves can be pathways through potential barriers and baffles. ***The purpose of this study is to (1) evaluate the effect of such LDB and other ichnofossils in continental deposits as macropores and macrochannels that can affect reservoir interconnectivity and the integrity of seal characteristics as barriers or baffles; and (2) determine up-dip to down-dip ichnofossil assemblages change in eolian-dominated settings.***

Project Description

Preliminary study has identified LDB, interpreted to have been constructed by vertebrates of different sizes and likely from different families or orders, within pedogenically modified eolian and sabkha depositional environments at two locations in the CMS at Moki Dugway (Figure 1) and the southern part of Comb Ridge (Figure 2), southeastern Utah. LDB at Moki Dugway are in interdune and fluvial deposits between eolian dune deposits (Figure 3); in the southern part of Comb Ridge LDB occur in interbedded sandstone, siltstone, mudstone, and gypsum beds, but prominently found in pedogenically modified clastic interbeds (Figure 4). Burrows of vertebrates, as well as bioturbation by invertebrates and plants indicate wetter phases that interrupt eolian processes.

The Lower Permian CMS is a 200–300 m thick, predominately eolian sandstone located in the central portion of the Colorado Plateau in southeastern Utah (Baars, 1962; Langford and Chan, 1989; Mountney and Jaggar, 2004). Deposition on the Colorado Plateau was sourced from the Uncompahgre uplift to the northeast during the Pennsylvanian and Permian (Mack, 1977). The CMS is interpreted as NE–SW-trending coastal erg deposits that paralleled the paleoshoreline (Loope, 1985; Langford and Chan, 1989; Mountney and Jaggar, 2004).

The LDB are identified preliminarily as vertebrate burrows of probable amphibian or reptile origin (Hasiotis and Rasmussen, 2010). The architectural morphology of the burrows overall is simple. Burrows are subhorizontal and at ~10–15 degrees from horizontal. The longest exposed burrow is nearly 50 cm. Burrow shape is elliptical and ~5–15 cm in diameter and ~2.5–5 cm in height, with the majority larger in diameter, rather than smaller. The surficial morphology preserved on the burrow walls is mostly smooth, however, the best-preserved burrows contain nearly 1-cm-diameter knobby surfaces, and scratch marks that are longitudinal to the burrow wall, as well curvilinear as C-shaped scalloped marks. LDB discovered to date in outcrops above the Valley of the Gods vary from simple to moderately complex in architectural morphology, as simple branched networks rather than three-dimensional boxwork. The longest exposed burrow is nearly 150 cm. Burrows are strongly subhorizontal and at ~5–10 degrees from horizontal, with a short, J-shaped entrance. Burrow shape is strongly elliptical, and diameter ranges from ~25–50 cm in diameter and ~5–10 cm in height; these dimensions likely indicate that the original diameter was also strongly elliptical. The surficial morphology preserved on the burrow walls varies from smooth to finely knobby and hummocky surfaces.

Lithofacies will be described and stratigraphic sections constructed for each study area. Plant and invertebrate traces, especially those associated with the LDB, will be documented, described, and assigned to appropriate ichnogenera. Don Rasmussen will be involved with fieldwork and provide guidance for stratigraphic and sedimentologic interpretations. The abundance, type, and distribution of rhizoliths will be used in conjunction with pedogenic features to determine the paleoenvironmental and paleohydrologic conditions in both up-dip and down-dip outcrop areas. All LDB observed will be photographed and their architecture and surficial morphology described and documented. Petrographic thin sections of the structures and their host rock will be made to better determine fill and surrounding rock lithologies. A database of the quantitative architectural and surficial measurements of the LDB will be made, and Spearman's Spearman's Rank Correlation Coefficient used to compare their qualitative characteristics to general architectural and surficial morphology of established biotic and abiotic structures in order to accurately determine their origin, as well as their distribution within lithofacies associations in the Moki Dugway and Comb Ridge areas where carbonate-dominated cements and pedogenic fabrics are replaced by gypsum, respectively. All of these data on bioturbation patterns—field and lab analyses—will be tied to the sedimentary and pedofabric patterns to build ichnocoenoses (trace communities) and ichnofacies models and define the relationship between grain size, facies, biogenically mediated porosity and permeability trends in eolian-dominated settings. Through this systematic analysis, we expect to find marked differences in trace fossil associations with respect to grain size and type, sorting, sedimentary structures, and pedogenic fabrics across depositional strike.

Deliverables

LDB and associated invertebrate and plant trace fossils are important in eolian depositional settings for: 1) reconstructing, interpreting, and subdividing environments of deposition

(EOD); 2) serving as Kv and Kh pathways through fine-grained lithofacies typical of baffles or barriers to fluid flow. Phase 1 of this research will provide 1) a photocatalog of trace fossils and lithofacies associations, and 2) the up-dip to down-dip changes in EOD, ichnocoenoses, and pedogenic characteristics of eolian-dominated depositional systems.

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***Figure 1**. Cedar Mesa Sandstone at Moki Dugway near Mexican Hat, Utah, composed of interbedded eolian sandstone and fluvial sandstone, siltstone, and mudstone.*

***Figure 2**. Cedar Mesa Sandstone at Comb Ridge near Mexican Hat, Utah, composed of interbedded eolian gypsum and fluvial sandstone, siltstone, mudstone, and reworked gypsum.*

***Figure 3**. Mega-diameter burrows at Moki Dugway penetrated into interdune and fluvial deposits and later filled with eolian sand from above.*

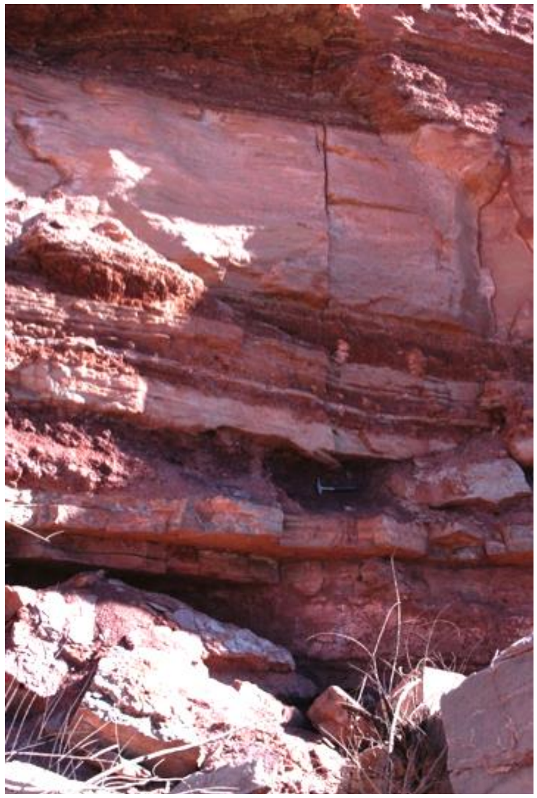

Figure 4. Large-diameter burrows (above the rock hammer for scale) and gypsic paleosols (layers with white rhizocretions) at Comb Ridge penetrated into and fluvial mud and later filled with fluvial sand from above.

Ichnology and Paleopedology in Mixed Carbonate and Siliciclastic Environments: A Study of the Upper Pennsylvanian (Virgilian) Halgaito Formation, Southcentral Utah

Stephen T. Hasiotis and Don Rasmussen

SUBSURFACE APPLICATION: Pennsylvanian reservoir and source rocks and their time equivalents in the Paradox basin oil and gas fields
STATUS: Phase 2 of this project; expanding on previous thesis and preliminary local results.
TIMING: 2 (MS student)–4 (PhD student) years
FUNDING: Seeking funding from sponsors

Purpose

Ichnofossils provide detailed information about the depositional history of mixed carbonate and siliciclastic systems. Such systems are common in the geologic record, but few studies have focused on them. Invertebrate organisms react to changes in climate and depositional environmental settings, producing specific patterns in bioturbation that reflect specific biophysicochemical characteristics used to interpret subenvironmental settings and changes in eustatic sea level in mixed carbonate and siliciclastic strata. Changes in lithofacies-ichnologic associations impact the resultant bioturbation textures that modify the original horizontal and vertical effective porosity and permeability. ***Phase 1 of this study aims to better understand these complex systems through the integration of trace fossil, lithofacies, and pedofacies associations of the Upper Pennsylvanian (Virgilian) Halgaito Formation to (1) define and subdivide environments of deposition, (2) develop ichnopedofacies models to help predict vertical and lateral facies changes produced by changes allocylic and autocyclic controls, and (3) place these mixed carbonate-siliciclastic stratea in a sequence stratigraphic. Understanding the depositional history of mixed carbonate and siliciclastic systems will help reduce and constrain uncertainty by models for larger scale regional architecture, and for identifying targets for oil and gas production.***

Project Description

The Upper Pennsylvanian Halgaito Formation is part of the Pennsylvanian Hermosa Group that thin westward, across southeast Utah from the Uncompahgre uplift and interfingers with marine carbonates in the west toward the San Rafael Swell (e.g., Baars, 1962; Cole et al., 1996; Montgomery et al., 1999; Rasmussen and Rasmussen, 2009; Rasmussen, 2014). The Hermosa Group grades toward the San Rafael Swell, and is equivalent to the lower Cutler Group. The Halgaito Formation is time-equivalent with the upper Hermosa Group and contains a succession of thinly interbedded siliciclastic and carbonate deposits (Figure 1) (Kunkle, 1958; Baars, 1962; Peterson and Hite, 1969). Donald Rasmussen is currently revising the stratigraphic nomenclature of the Cutler Group in a series of papers and maps; he will be working with my student(s) and me on these units (Rasmussen and Rasmussen, 2009; Rasmussen, 2014).

The Halgaito Formation is a thinly bedded, mixed carbonate and siliciclastic unit located near Mexican Hat in southcentral Utah. The Halgaito Formation contains intercalated carbonate and siliciclastic deposits that represent shallow marine to coastal plain settings and record relatively rapid changes in sea level. Continental deposits include thin to thick, weakly to well-developed paleosols associated with alluvial plain deposits. Intervals of marine carbonate deposits also show pedogenic overprinting, as well as modification due to penetrative soil formation.

Marine trace fossils are well studied and have been used to interpret a variety of paleoenvironments (e.g. Clifton and Thompson, 1978; Ekdale and Bromley, 1984). Marine organisms react to a variety of physicochemical conditions (i.e., medium, nutrients content, salinity, turbidity, temperature, oxygen content) and, thus, their traces can be used to interpret depositional environments (e.g., Ekdale and Bromley, 1984; Hasiotis and Platt, 2012). Such interpretations must be done cautiously, as many marine trace fossils can be found in multiple environments (e.g., Ekdale and Bromley, 1984; Hasiotis, 2006) Trace fossils are common in continental settings (e.g. Hasiotis, 2006; Hasiotis and Platt, 2012), and are created by organisms that react to a different suite of physicochemical controls that produce trace fossils indicative of terrestrial and freshwater settings. These include soil moisture and saturation, temperature, seasonality, and precipitation (Hasiotis, 2006; Hasiotis and Platt, 2012).

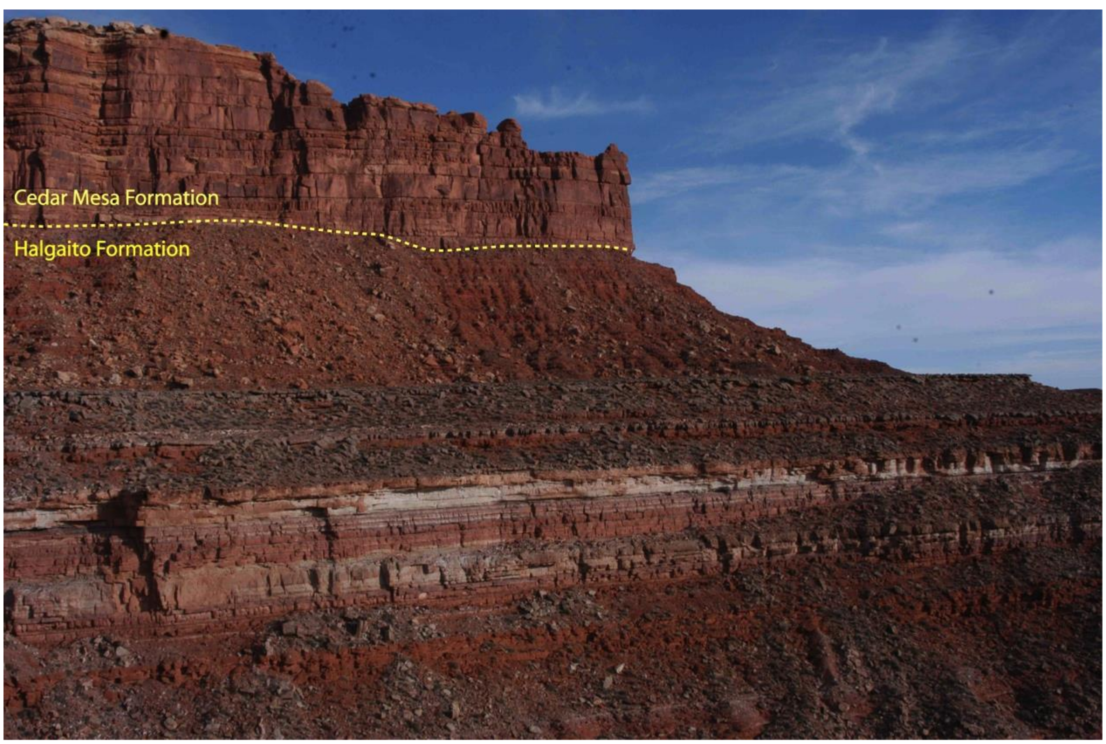

***Figure 1**. Photograph of the Halgaito Formation and younger Cedar Mesa Formation in outcrop taken near Mexican Hat, Utah.*

***Figure 2**. Photograph of clam traces in the Halgaito Formation taken near Mexican Hat, Utah.*

This project will be accomplished through field research and laboratory investigations to characterize the ichnofossils in both the carbonate and siliciclastic deposits within the Halgaito Formation. Fieldwork will consist of measuring several stratigraphic sections for vertical and lateral variations and correlations. Sections will be logged spatially with GPS. Beds will be described sedimentologically and lithologically and assigned to lithofacies. Photographic mosaics will be constructed to illustrate the architecture graphically, and photographs will be taken of all relevant small- and large-scale features. Paleosols in fine-grain strata will be trenched to examine morphology, remnant sedimentary structures, and ichnofossil assemblages. They will be classified using the U.S. Soil Taxonomic System. Grain-size fractionation will be estimated in the field using standard soil texture methods.

Laboratory work will use X-ray diffraction analysis (XRD) and thin-section descriptions. Clay content and mineralogy will be determined through XRD with samples taken from each trench or horizon. Thin sections will be used to further examine the sedimentary structures, as well as to identify microscale biologic features, such as borings. Thin-sections will be 24 by 46 mm in size and be impregnated with blue epoxy to increase the durability of paleosol samples. Sodium cobaltinitrite staining will also be used to identify the relative abundance of potassium feldspars, a common clay-forming mineral in soils.

Deliverables

Ichnological and pedological studies in the mixed carbonate-siliciclastic strata of the Halgaito Formation are important as they provide: 1) important clues to interpreting environments of deposition, as well as syndepositional and postdepositional conditions; 2) information on how bioreworking affects and modifies the original depositional fabric and texture; 3) biomodified textures have different porosity and permeability than the primary depositional matrix. Research results generated in Phase 1 will provide: 1) models of trace fossil, lithofacies, and pedofacies associations, 2) interpretations of autocyclic and allocyclic controls of stratal patterns, grain type and texture, and changes in eustatic sea level, and 3) a sequence stratigraphic framework for local and regional architecture of the mixed carbonate and siliciclastic strata. This research will provide new conceptual models for the extent and significance of ichnology and paleopedology in the reconstruction of depositional environments and the modification of depositional porosity and permeability.

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Sequence Stratigraphy and Reservoir Character of Miocene Tropical Heterozoan-Limited Photozoan Outcrop Analog Systems in the Caribbean

Evan K. Franseen and students

SUBSURFACE APPLICATION: Upper Oligocene-Miocene carbonate systems in the Caribbean are dominated by heterozoan carbonates along with photozoans that tolerate turbid water, mesotrophic, and cooler water conditions (limited photozoan association). Outcrops in the region are direct analogs for Oligocene-Miocene heterozoan reservoirs in the Caribbean, such as the Perla giant gas field (offshore Venuzuela), and Cenozoic heterozoan-limited photozoan reservoirs in the Indo-Pacific (e.g. Ca Voi Xanh field, offshore Vietnam). Lessons from the outcrops can be applied to other heterozoan reservoir systems in the ancient.
STATUS: Part of ongoing research program. Targeted projects of 2-4 years upon funding. Project in Jamaica and Dominican Republic described below started fall of 2015. Interim results are available to sponsors.
TIMING: Ongoing research program; Jamaica-Dominican Republic project to be completed end of 2020.
FUNDING: Seeking funding

Purpose

Heterozoan carbonate systems are increasingly being recognized as important petroleum reservoirs in the rock record. Although research on heterozoan systems has accelerated over the last two decades, we still lack understanding of controls on facies types and distribution, stratigraphic architecture, and reservoir character. The understanding of heterozoan systems in low-latitude tropical regions is especially lacking. They are increasingly being recognized in areas that are affected by excess nutrients, and turbid water. In addition, some systems forming under these conditions can contain abundant photozoan components. However, the photozoan biota that are dominant are only those that tolerate higher nutrients, more turbidity, and reduced temperatures (herein termed "limited photozoan association"). These tropical heterozoan -limited photozoan association systems are predominantly composed of loose grains and form non-rimmed platforms, ramps, and deeper-water systems composed of sediment gravity flows. ***During the Upper Oligocene-Miocene, upwelling throughout the Caribbean resulted in regional development of heterozoan-limited photozoan carbonate systems, some of which form significant reservoirs, such as the Perla giant gas field (offshore Venezuela), and are targets of ongoing exploration in the region. Caribbean systems exposed in outcrops are direct analogs for the Caribbean reservoir systems and are similar to other low-latitude tropical systems, such as Cenozoic reservoirs in the Indo-Pacific region (Ca Voi Xanh field, offshore Vietnam).***

Project Description

This project is a continuation of a research program that has been studying Oligocene-Miocene systems in the Caribbean. Previous work studied outcrops in Puerto Rico and the Dominican Republic (e.g. Ortiga-Ariza et al., 2015). This project is focused on excellent outcrop exposures in the Dominican Republic and Jamaica. These exposures allow us to construct detailed sequence stratigraphic frameworks; evaluate the effects of relative sea-level fluctuations on heterozoan-limited photozoan facies distributions and patterns: evaluate different substrate paleotopography on the carbonate systems (e.g. development of ramps versus downslope systems consisting of transported facies); evaluate effects of regional processes on facies composition (e.g. upwelling); evaluate other potential controls, such as the influence of land-sourced siliciclastics (and possible associated nutrients), and; evaluate controls on, and nature of, reservoir character of the various heterozoan-limited photozoan systems.

The Dominican Republic area consists of Miocene-Pliocene mixed siliciclastic-carbonates that are well exposed along road cuts for ~155 km (Figure 1). Overall, this appears to be a gently sloping ramp system. However, locally, some lower sequences are deposited on the flanks of a basement high and consist predominantly of heterozoans and large benthic foraminifera (LBF). Upper sequences show a pattern of heterozoan-dominated facies in bases of sequences and an increase in photozoans (and appearance of corals) in upper parts of sequences, which appear to be related to transgressions and regressions. The focus of study will be on the heterozoan-LBF sequences (System 1, Figure 1), documenting controls on deposition and reservoir character, including construction of a 3-D petrel model.

Jamaica has Eocene-Miocene proximal to distal ramp systems that are exposed for ~50 km along new road cuts, and nearby quarries (Figure 2). These outcrops show various patterns of photozoan (including coral) and heterozoan abundances, but have not been studied in detail in terms of sequence stratigraphy, controls on deposition, and reservoir character. The deposits in both the Dominican Republic and Jamaica developed on variable paleotopography and show evidence of both in-place deposition, and downslope deposition of transported shallow-water carbonates.

Methods of study for each of the areas include: measuring stratigraphic sections, physically tracing strata and surfaces, documenting facies, sedimentary structures, and diagenetic features to determine depositional environments, construct sequence stratigraphic frameworks, and evaluate reservoir character; collect and evaluate structural data for paleotopographic reconstruction; collect data on geometries, thicknesses, and lateral extent of major facies and propose how they react to fluid flow (are they baffles, conduits, etc.); collect samples for all major facies for core plug porosity and permeability data to quantitatively determine which facies have the best reservoir character; use field, thin section and petrophysical data to construct reservoir analog models in Petrel.

Deliverables

Specific deliverables for the project include maps, stratigraphic sections, cross sections, sequence stratigraphic frameworks, data on the various controls for the Dominican Republic and Jamaica systems being studied, porosity and permeability data bases of major facies, 3-D reservoir character models constructed using Petrel. Overall, the results of this study provide useful information for controls on deposition and facies distribution, stratigraphic architecture, and developing predictive models for subsurface reservoirs.

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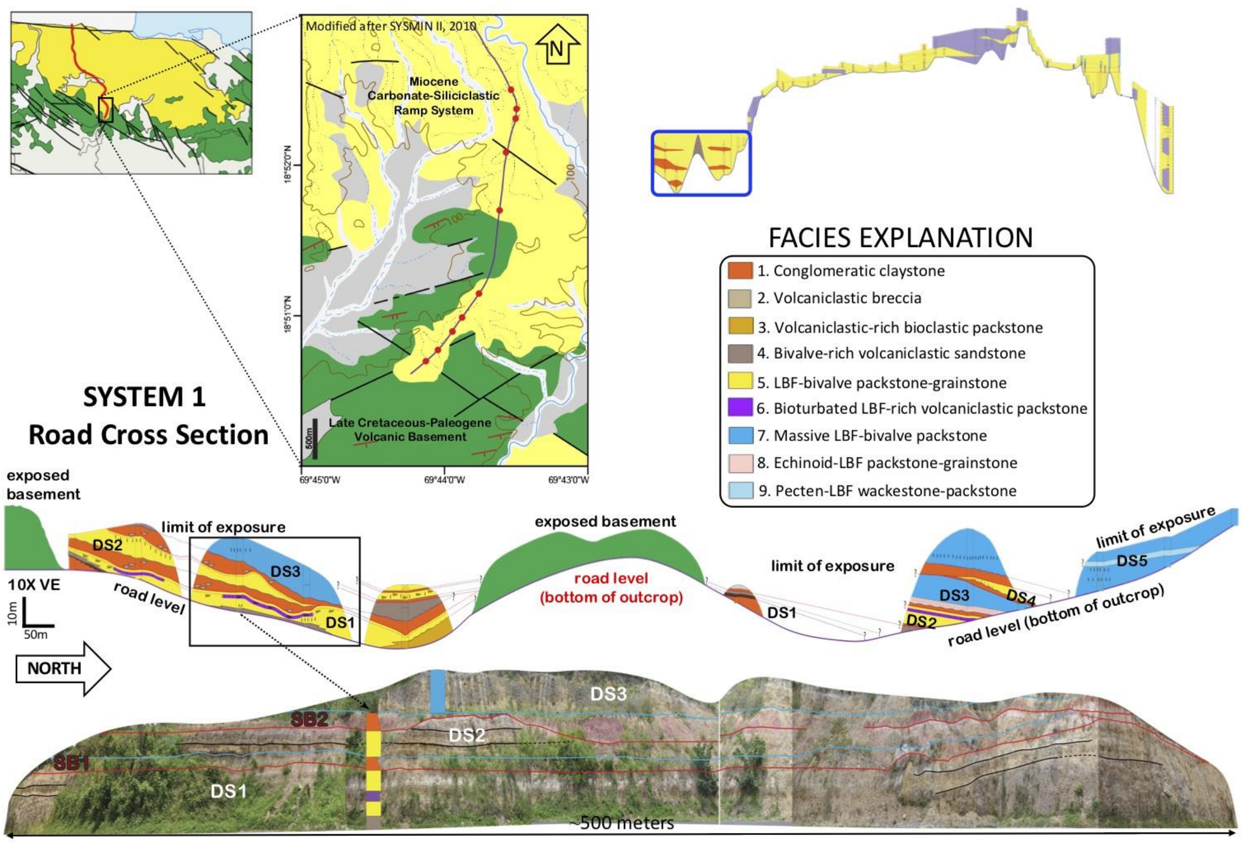

- Paleotopography preserved – Present-day elevation proxy for Miocene elevation, and dips of strata are primary and related to locations of volcanic highs

Figure 1. *Maps in upper left show Dominican Republic study area and locations of cross sections. System 1 is the focus of the study (lower cross section and roadcut exposure. Sequences capped by subaerial exposure surfaces and the heterozoan-LBF carbonate and mixed carbonate-siliciclastic facies indicate that variable substrate paleotopography and relative sea-level fluctuations were important controls on deposition.*

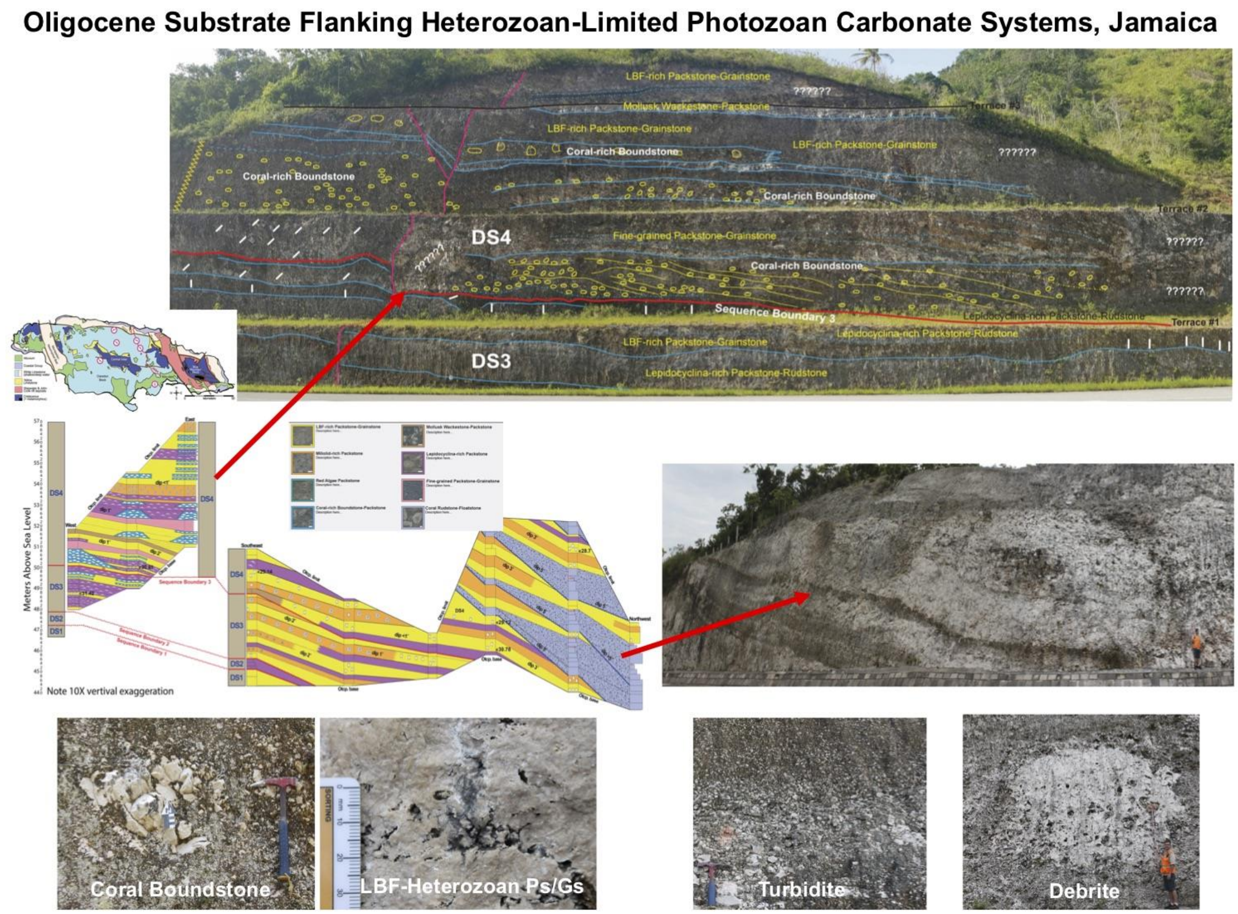

Figure 2. *Generalized geologic map (upper left diagram) of Jamaica showing generalized stratigraphy and ages of units. The Oligocene-Miocene carbonate sequences developed on the flanks of Cretaceous-Eocene substrate paleohighs. The left part of the cross section and upper outcrop photo show in-place LBF-heterozoan and coral boundstone facies developed on gently sloping substrates. The right part of the cross section and right photo show several turbidite and debrite units (gray color on cross section) composed of LBFs, heterozoans, and coral boundstone transported downslope from shallow water.*

Controls on Mississippian (Osagean) Inner Ramp Heterozoan Carbonate & Biosiliceous Deposits in a Midcontinent Setting

Evan K. Franseen, and student

SUBSURFACE APPLICATION: The specific rocks of this proposed study form reservoir systems in the midcontinent. These types of rocks also form Mississippian reservoirs in other North America locations such, as the Williston Basin.
STATUS: Ongoing research; several projects complete and results reported to sponsors
TIMING: 2 years
FUNDING: Seeking funding

Purpose

Osagean-Meramecian time was characterized by extensive development of biosiliceous and carbonate accumulations in some areas of North America (Lowe, 1975; Gutschick and Sandberg, 1983). During this time a low-latitude, shallow tropical sea covered most of the southern North American continent. In low-latitude, tropical systems, shallow-water carbonate facies would be expected to contain abundant Photozoan Association components. Importantly, photozoan components are notably absent in low-latitude Osagean ramp settings in the Midcontinent, including inner ramp settings. Instead the facies are dominated by Heterozoan Association carbonates and siliceous sponge-spicule facies. The system of interest forms the Mississippian Lime play. Most work has focused on ramp-margin areas, whereas inner-ramp areas remain less studied. Not only are inner ramp areas important in that they are reservoir targets, but these areas are important for understanding controls on the entire ramp system. An initial study of the Schaben field in Ness County, an inner ramp location that produces from sponge spicule-rich facies, suggested regional upwelling as a major control for the dominance of heterozoan and biosiliceous facies across the ramp system (Franseen, 2006). ***Additional study of inner ramp areas is important for further evaluation of upwelling as a control. Distinguishing between regional and local controls on facies types and distribution on the entire ramp system can provide predictive capabilities for exploration and exploitation of unconventional and conventional reservoirs.***

Project Description

Paleogeographic studies place Kansas at about 20° S latitude (Fig. 1). Osagean deposition in the region was characterized by carbonate and biosiliceous facies that were deposited on a gently sloping ramp to the south, with the ramp edge bordering the Anadarko basin located near the Kansas-Oklahoma border. Previous detailed studies of Osagean strata in Kansas have focused on shelf-margin areas where thick accumulations of sponge-rich chert deposits occur (informally termed "chat") and form significant reservoir facies known as the Mississippian Lime Play (e.g. Montgomery et al., 1998). Osagean strata in Kansas are cherty, partially dolomitized skeletal (especially crinoidal) packstone and grainstone and cherty, partially dolomitized and argillaceous wackestone and mudstone (Watney et al., 2001; Franseen, 2006). Inner ramp areas are characterized by siliceous sponge-dominated wackestones and packstones (with and without evaporites) and echinoderm/bryozoan packstones and grainstones.

Several hypotheses are proposed if regional upwelling and sea level are dominant controls: 1) expect less biosiliceous deposits and redistributed silica away from upwelling areas, and grainstone-packstones as a dominant reservoir facies. 2) Relative sea-level history may play a major role for reservoir facies distribution. Transgressions can facilitate upwelling water reaching inner ramp areas (Lowe, 1975) thereby promoting biosiliceous facies in those locations. Regressions may result in less, or no upwelling and less or no silica across the ramp. Under these conditions, photozoan facies may be more abundant, including ramp-margin areas.

Subsurface well logs, cores, structural data, and literature examples will be analyzed for facies distribution in inner ramp locations near proposed upwelling areas along basin margins, as well as locations away from proposed upwelling areas. A sequence stratigraphic framework of inner ramp locations will be constructed by integrating core and subsurface well log data. This framework will be integrated with existing sequence stratigraphic frameworks for ramp margin and basinal areas to identify significant relative sea-level fluctuations. Facies types and distribution tied to sea-level rises and falls will be examined to determine if hypothesized rises result in abundant biosiliceous facies in inner ramp areas, and sea-level falls result in less biosiliceous facies in inner ramp areas, and if any photozoan components are present.

Deliverables

The outcome of this study will provide a better understanding of depositional environment and distribution of inner ramp lithofacies, and determining how sea-level changes, and other regional controls, such as upwelling, affect nature and distribution of reservoir facies. Paleogeographic maps showing inner ramp facies types and distribution in the continental U.S. will be created. Detailed cross sections depicting the sequence stratigraphic framework will be constructed to illustrate geometries and determine sea-level effects on facies. The results of this study will contribute to a better prediction of facies distributions to delineate areas of additional conventional and unconventional gas reservoirs in inner ramp areas in detail, and across the entire ramp system in general.

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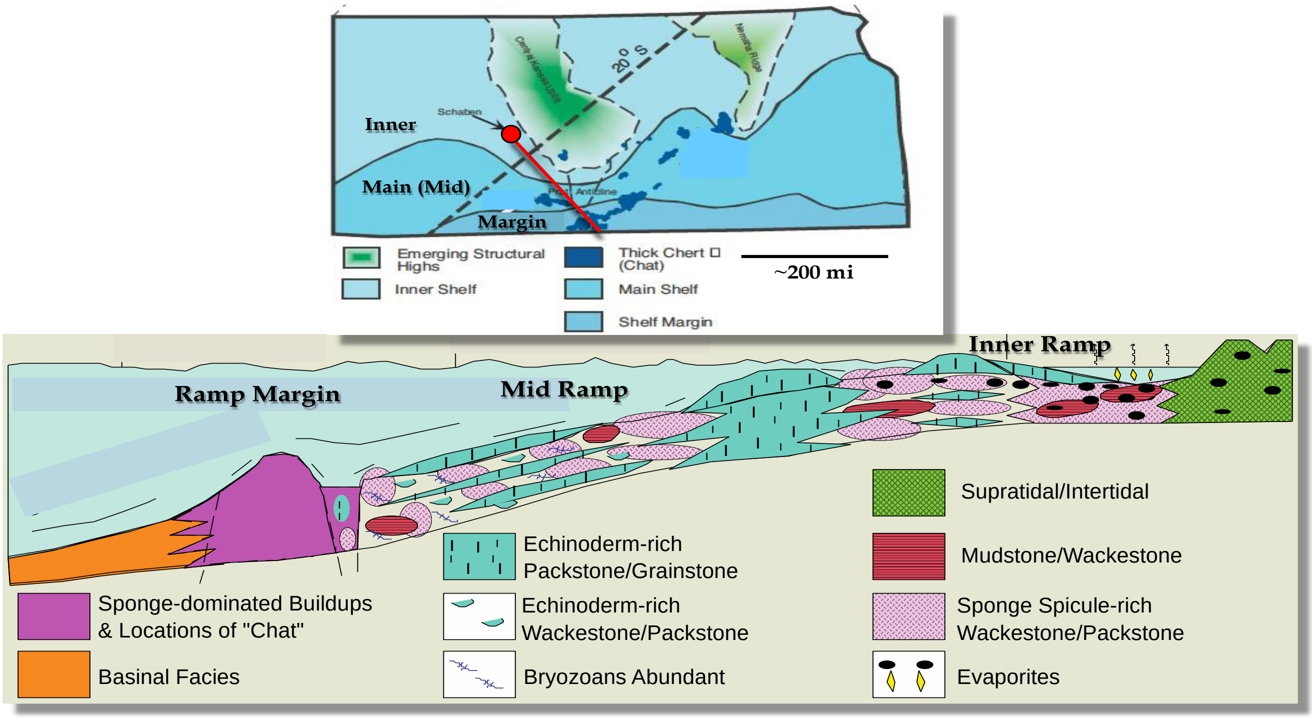

Figure 1. *Paleogeographic map of Kansas and schematic inner ramp to ramp margin cross section.*

Build-and-Fill Sequences in Carbonate-Dominated Systems: Towards Predictive Models for Reservoir Characterization

Evan K. Franseen and Robert H. Goldstein

SUBSURFACE APPLICATION: We are studying and documenting Build-and-Fill sequences throughout the rock record. Examples of Build-and-Fill sequence reservoirs identified to date include the Upper Jurassic Arab-D reservoir in Saudi Arabia, the Lower Cretaceous Shu'aiba reservoir in Oman, and Upper Miocene-Pliocene reservoirs in Indonesia.
STATUS: Ongoing long-term research; initial concepts developed and reported to sponsors
TIMING: Ongoing; targeted projects of 2-4 years upon funding
FUNDING: Seeking funding

Purpose

Concepts on cycles, cyclothems, and cyclostratigraphy in carbonate and mixed carbonate/siliciclastic systems have been developed and debated for years, but much remains to be learned, and current sequence stratigraphic models do not adequately address the nature and controls on formation of these types of strata. Our work is focused on systems in the geologic record where thin sequences (10's of meters thick) are prevalent, drape topography, and maintain similar thickness throughout wide geographic areas, but have a complex internal architecture of building and filling relief. ***Many of these form important reservoirs and our goal is to develop a detailed understanding of controlling factors for development of better predictive models to better maximize exploration/exploitation efforts.***

Project Description

Our intial phase of study has been through projects targeting build-and-fill nature in ice-house carbonate-dominated systems of the Pennsylvanian, Permian, and Miocene (e.g. Mckirahan et al., 2003; Washburn and Franseen, 2003; Franseen and Goldstein, 2004, Emry et al., 2006; Franseen et al., 2007; Fairchild et al., 2008; Lipinski et al., 2008; Goldstein et al., 2013; Lipinski et al., 2013; Lechtenberg et al., 2016). The systems we are targeting exhibit thin sequences (10's of meters thick) that maintain similar thickness throughout wide geographic areas, despite having a complex internal architecture. Our initial results indicate that "build-and-fill sequences" develop in settings in which carbonate productivity is less than optimal, leading to underfilled accommodation and incipient drowning during rises, and subsequent fill of low areas, typically during highstand or falling sea level. Fine-grained siliciclastics and adverse paleoceanographic conditions may inhibit carbonate productivity and lead to build-and-fill sequence development.

In icehouse systems, the build-and-fill zone develops in medial positions on broad shelves/ramps, and in inner platform/lagoon positions on high-standing rimmed platforms. Icehouse build-and-fill sequences result from the interaction of high-amplitude, high-frequency sea-level fluctuations with paleotopography and sediment dispersal processes. In greenhouse systems, the build-and-fill zone appears to develop only in inner platform/lagoon positions on high-standing rimmed platforms, where sea-level fluctuations and relatively shallow water interacts with paleotopography in areas of suppressed carbonate productivity.

The systems studied to date indicate that given accommodation in the build-and-fill zone, topographic highs may be favored areas to build relief by boundstone and grainstone. The fill phase may be favored by limited accommodation. Localized deposition of delta-like siliciclastics may modify relief in paleo-low areas, given a paleotopographic focus. Where shallow-water conditions intersect complex topography, currents may be focused, depositing grainy carbonate and siliciclastic facies in lows. If energies are too high along topographic highs, boundstone/wackestone/packstone facies may accumulate (fill) in the topographic lows where current energies are weaker.

The second phase of study has included additional field studies and extensive literature search, to gain a better understanding on prevalence of build-and-fill architecture in the rock record, ranges of build-and-fill character, and controlling factors that result in build-and-fill. The preliminary results indicate that build-and-fill architecture occurs: 1) throughout the rock record, 2) in icehouse, greenhouse, and transitional systems, and 3) in middle portions of shelves and ramps, and interior portions of rimmed platforms that experience highest rates of sea-level change between sea-level highstand and lowstand positions. Examples identified from our studies and in literature are direct analogs for producing subsurface reservoirs.

The proposed third phase will further test and refine the conceptual model towards a predictable model and will work with KICC sponsoring companies to identify subsurface targets in which documentation of build-and-fill systems can aid in reservoir characterization.

Deliverables

Deliverables for the project include maps, stratigraphic sections, cross sections, copies of theses, copies of presentations, and quantitative data on the various projects and systems that have been completed to date, and those that are currently being studied or will be studied in the future. Current deliverables also include the current conceptual model of build-and-fill sequences, and literature review of outcrop and subsurface systems (including reservoirs) that show characteristics of build-and fill.

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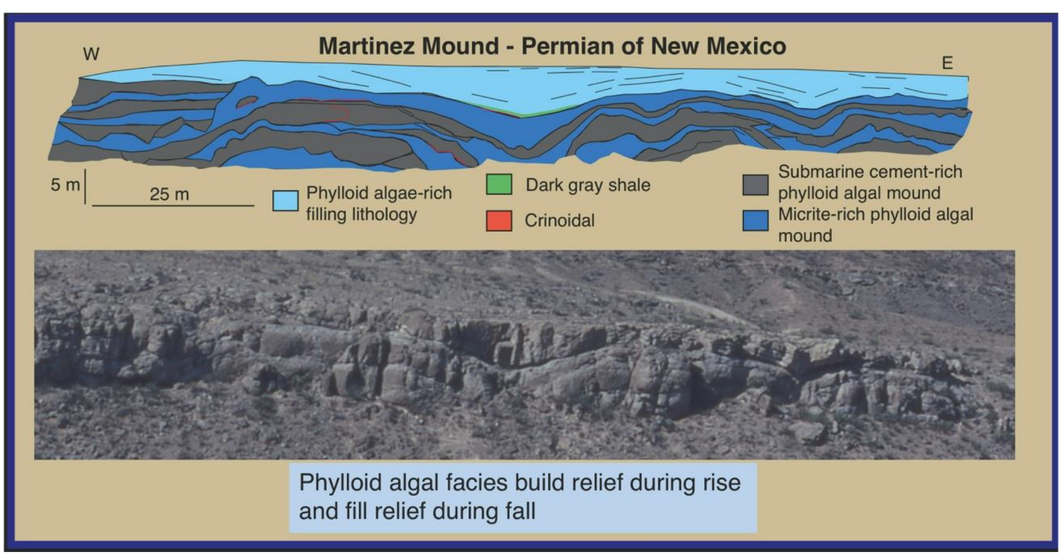
Figure 1. *Location of build-and-fill zone in ramps and rimmed platform settings*

Figure 2. *Example of phylloid algal facies building and filling relief in the Permian of New Mexico.*



Diagenetic Controls on Porosity and Permeability in Carbonates

After deposition, carbonates are modified by diagenesis that can markedly alter reservoir properties. As such, studies investigating post-depositional alteration of carbonates can provide novel insights into complex patterns of reservoir quality common in carbonates. Systematic study of diagenetic process and response is necessary. Traditional hydrozone approaches are being reevaluated in the context of new understanding of diagenetic reactions. Examples of some current and pending projects include:

Radiometric Dating to Constrain Timing of Diagenetic Events in the Permian Basin

Sahar Mohammadi, Robert H. Goldstein, Andreas Moeller

SUBSURFACE APPLICATION: Permian Basin conventional and unconventional reservoirs including Grayburg-San Andres, Strawn, Canyon, Cisco, Wolfcamp, Bone Spring
STATUS: Project Proposed
TIMING: Upon funding
FUNDING: KICC

Purpose

Studies of diagenetic history of reservoir rocks in the Permian Basin show a complex paragenesis. In both the Delaware and Midland basins, there is strong evidence for reflux of Permian residual evaporite brines. Burial leads to overpressuring and "beef" calcite in some unconventional reservoirs, and later fluid flow commonly involves a hydrothermal component, which may have started with Laramide deformation, and continued into the "volcanic phase" and basin and range tectonism. This project will use radiometric dating to establish the timing of calcite and anhydrite precipitation from (1) brine reflux, in order to provide fundamental constraints on the longevity of brine penetration into the subsurface. This will provide the first fundamental data on the rate at which basins are charged with concentrated brines, and it will evaluate the diagenetic impact of such fluid penetration. In addition, the study (2) will evaluate the timing of formation of "beef" calcite. Numerous studies have proposed that "beef" calcite represents the development of overpressure in unconventional reservoirs. Establishing absolute timing of beef precipitation will aid in understanding the mechanisms of overpressure development and provide new constraints on burial history. Finally, many areas of the Permian Basin show evidence of multiple events of migration of hydrothermal fluids (3) that have had an impact on hydrocarbon migration, thermal maturity, and porosity distribution. Tectonic drivers of fluid flow are essentially unknown, and radiometric dating of calcite and dolomite associated with these events would constrain if the drivers are Laramide, "volcanic phase" of Basin and Range in origin. Determining that timing will allow companies to predict reservoir properties on the basis of structural controls that are resolvable using geophysical techniques.

Project Description

Previous studies of diagenetic history of the Indian Basin Field, northwest shelf of the Delaware Basin, have illustrated a complex diagenetic history dominated by hydrothermal fluid flow. This hydrothermal system was proposed to begin during Laramide deformation (Hiemstra and Goldstein, 2014). In contrast, other areas of the central Delaware basin (Wolfcamp) show evidence for relatively closed systems (Poros et al., 2014); where there is dominance of beef calcite. There is also an early fracture set (and associated diagenetic phases) proposed to be related to burial and the Ouachita-Marathon orogeny, and a late fracture set (and associated diagenetic phases) proposed to be related to Basin-and-Range deformation. In contrast, a recent study of the Wolfcamp in the eastern Midland Basin proposes an open system, with a stage of reflux followed by a complex history of hydrothermal fluid flow that begins with Laramide deformation (DeZoeten, 2018). Obtaining absolute dates on the already-established paragenetic histories from these studies will be key in determining the timing of overpressure, refining the burial history, and determining the tectonic drivers of fluid flow in the Permian Basin.

Advances in laser probe ICP-MS and development of reference standards for U/Pb dating of calcite facilitate the rapid radiometric dating of certain calcites and dolomites. (Rasbury and Cole, 2009). Recent work on radiometric dating of calcite from the Permian Basin shows promise in identifying calcite cementation that are related to events of hydrothermal fluid flow (Figure 1; Decker et al., 2018). These events are closely related to Laramide and later deformation, uplift, and magmatic activity (Cather et al., 2012).

This project will include petrography, laser probe ICP-MS and thermal ionization mass spectrometry to establish timing of diagenetic events in already established paragenetic frameworks. This will be used to evaluate the timing and distribution of brine reflux, the timing of formation of "beef" calcite to constrain timing of overpressure and burial history, and the tectonic drivers for hydrothermal fluid flow as a means of evaluating structural controls on reservoir properties.

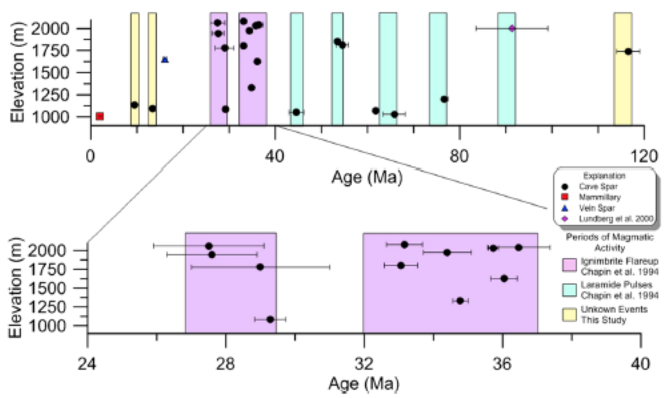


Figure 1. *U/Pb ages of calcite from the Guadalupe Mountains plotted versus elevation. Note that age spectrum includes the Laramide Orogeny, Volcanic Phase, and Basin and Range deformation (after Decker et al, 2018).*

Deliverables

- Radiometric dates of diagenetic phases from the Indian Basin, Wolfcamp from the central Delaware Basin, and Wolfcamp from the eastern Midland Basin
- Refined burial histories for the Permian basin and interpretations of timing of overpressure
- Hypotheses for structural/diagenetic control on hydrothermal overprint on reservoir properties in Permian Basin

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Radiometric Dating of Carbonate Cements: Evaluating the Drivers of Fluid Flow and Porosity Evolution in Midcontinent Reservoirs

Sahar Mohammadi, Robert H. Goldstein, Andreas Moeller

SUBSURFACE APPLICATION: Mississippian, Pennsylvanian, Arbuckle Group
STATUS: Project Proposed
TIMING: Upon funding
FUNDING: KICC

Purpose

This research proposes to develop U/Pb dating of diagenetic phases to test hypothetical drivers of fluid flow in the Midcontinent. The initial study will focus on calcite and dolomite that has already been placed into a paragenetic context in Oklahoma and Kansas. The goal is to relate fluid migration and porosity evolution to tectonic and stratigraphic drivers, with the ultimate goal of predicting reservoir properties from structural setting identifiable using geophysical techniques.

Project Description

Carbonate reservoirs of the southern Midcontinent comprise important conventional and unconventional reservoirs in North America (Milam, 2013). These rocks have been affected by both pervasive and localized fluid flow (Wojcik et al. 1997; Gregg and Shelton, 2012). There is a stratigraphic control as well as structural controls on fluid migration (e.g. Poteet et al., 2018), including an event of low-temperature brine reflux, multiple events of advective hydrothermal fluid flow, and events of localized, structurally controlled hydrothermal fluid flow. These complex fluid flow events had an impact on localized reduction of porosity through cementation, creation of porosity through dissolution, and hydrocarbon migration. Without understanding the controls on fluid flow, and impact on reservoir properties, reservoir quality will remain difficult to predict.

This project seeks to evaluate the timing of fluid flow in areas of Oklahoma and Kansas, where a detailed paragenesis, isotopic and fluid inclusion data set has already been established in Ordovician-through-Pennsylvanian strata (Goldstein et al. 2018; Mohammadi et al., 2018 a,b). Previous preliminary studies dating diagenetic events have already demonstrated an event of Permian reflux, later advective hydrothermal fluid flow associated with the Ouachita system, and localized hydrothermal fluid flow, possibly resulting from Laramide structural reactivation and fault pumping (Table 1).

This study will focus on developing techniques that will lead to successful radiometric dating (U-Pb) of calcite and dolomite cements in the Berexco Wellington KGS 1-32 core in southern Kansas and various cores from the SCOOP and STACK areas of Oklahoma. Other studies have already established the potential of this technique for radiometric dating of calcite and dolomite (Rasbury and Cole, 2009). The project will include petrography, laser probe ICP-MS and thermal ionization mass spectrometry to establish timing of diagenetic events in already established paragenetic framework. This timing will be used

Region of Study	Hydrothermal Fluid Flow Mechanism	Specific Driving Forces	Interpreted Age of Hydrothermal Deposit	Radiometric or Paleomagnetic Dates	Authors
SE Kansas	Late-Paleozoic Ouachita orogeny	Progressively deeper thrust faulting	Late Pennsylvanian-Early Permian	N/A	Young, 2010
	Late-Paleozoic Ouchita orogeny and Laramide reactivation	Gravity flow from Ouachitas and Laramide fault pumping	Late Pennsylvanian-Early Permian and Late Cretaceous to Early Tertiary	N/A	Goldstein et al. 2018
	Late-Paleozoic Ouachita orogeny	N/A	Late Pennsylvanian	N/A	Wojcik et al., 1992, 1994, 1997
Central Kansas	Laramide reactivation	N/A	Laramide	N/A	Poteet et al., 2018
Northeastern Kansas	Laramide reactivation and hydrothermal fluid flow	N/A	Late Cretaceous to Early Tertiary	Apatite (U-Th)/He 67.3±4.4 Ma; 64.3±5.6 Ma	Blackburn et al. 2008
Western Kansas	Permian reflux followed by thermal overprint	Reflux followed by gravity drive out of Rocky Mountain foreland	End Permian reflux followed by Tertiary thermal overprint	250 Ma from reflux dolomite	Luczaj and Goldstein, 2000
Tri-State	Late-Paleozoic to Late-Mesozoic tectonic activity	Expelled pore fluids or gravity-driven flow	Pennsylvanian-Late Cretaceous	251±11 Ma; 137±3 Ma; 66±2 Ma; 39±2 Ma	Coveney et al., 2000
	Hot spot	Convection from hot spot reactivation and heating	Cretaceous	115±20 Ma	New preliminary data for this study
	Late Paleozoic Alleghenian-Ouachita orogeny	Gravity-driven flow	Late Permian-Early Triassic	251±11 Ma	Brannon et al., 1996b
	Late-Paleozoic Ouachita orogeny	N/A	>Late Jurassic	>183 Ma	Arne et al., 1992; Leach et al., 2001
SE Missouri	Late-Paleozoic Alleghenian-Ouachita orogeny	N/A	Late Pennsylvanian-Early Permian	286±20 Ma	Wisniowiecki et al., 1983; Leach et al., 2001
	Late-Paleozoic Alleghenian-Ouachita orogeny	N/A	Early Permian	273±10 Ma	Symons et al., 1998a; Leach et al., 2001
	Late Paleozoic Ouachita Orogeny	N/A	Permian	265 Ma from Illite	Hay et al. 1988

	Late Paleozoic Ouachita Orogeny	N/A	End Permian	250 Ma from post mineralization illite in Viburnum trend	Aronson reported in Rothbard, 1983
	N/A	N/A	Late Permian-Eocene	241±10 Ma; 203±10Ma; 100-50Ma	Arne et al., 1990; Leach et al., 2001
	N/A	N/A	Devonian	392±21 Ma	Lange et al., 1983; Leach et al., 2001
North Arkansas	Late-Paleozoic Alleghenian-Ouachita orogeny	N/A	Permian	265±20	Pan et al., 1990; Leach et al., 2001
	Laramide thermal waters along faults with methane oxidation	N/A	Eocene	52 ± 2 Ma for calcite	Tennyson et al. 2017
Central Missouri	Late-Paleozoic Alleghenian orogeny	N/A	Pennsylvanian	303±17 Ma	Symons and Sangster, 1991; Leach et al., 2001
NE Oklahoma	Late-Paleozoic Ouachita orogeny	Gravity-driven flow	Late Pennsylvanian	300±20 Ma	New preliminary data for this study
Central Tennessee	Late-Paleozoic Alleghenian orogeny	N/A	Late Permian-Early Triassic	245±10 Ma	Lewchuck and Symons, 1996
	Late-Paleozoic Alleghenian orogeny	Gravity-driven flow	Late Permian	260±42 Ma	Brannon et al., 1996a

Table 1. Summary of hypotheses and absolute dates for diagenetic events in the Midcontinent.

to develop hypotheses for control on fluid flow, that can in turn be used in conjunction with geophysical data, to develop structural models for which fault and fracture systems localized the diagenetic fluids that either enhanced or degraded reservoir properties at various stages of the 200+ million year diagenetic history in the Midcontinent.

Deliverables

- Development of radiometric dating techniques for establishing timing of calcite and dolomite precipitation.
- A workflow for evaluating calcite and dolomite for radiometric dating
- Absolute dates on various parts of the paragenetic framework in southern Kansas, SCOOP and STACK.
- Hypotheses for structural/tectonic and diagenetic control on reservoir properties in the Midcontinent

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Simulating hydrothermal fluid migration across the Midcontinent Paleozoic region of the United States

Andrea Brookfield, Sahar Mohammadi, Robert H. Goldstein

SUBSURFACE APPLICATION: Mississippian Midcontinent reservoirs, Osage, Meramec, Chester, Sooner Trend, SCOOP and STACK, Golden Trend
STATUS: Beginning stages of project
TIMING: Project proposed
FUNDING: Proposed to ACS-PRF

Purpose

Understanding the drivers and structure of past hydrothermal fluid flow in reservoirs is essential for the oil and gas industry. In the southern Midcontinent of North America, in-situ observations have allowed for the development of several hypotheses related to the origin and timing of hydrothermal fluid flow, and the impacts on the conventional and unconventional reservoirs. Significant advances in numerical tools capable of capturing the relevant flow processes related to these fluid flows, in addition to numerical inversion methods that conduct robust parameter estimation and uncertainty analyses, can rigorously test the reasonableness of these hypotheses. Despite computational advances that make these modeling approaches feasible, they have not been used to (re-) evaluate previous and new hypotheses related to the origin of hydrothermal fluid flow into reservoirs, ore, and other mineral deposits in sedimentary basins. In this work, we propose to utilize these recent modeling advances to test the plausibility of fast advective flow through fracture networks driven by tectonic valving and uplift associated with the Ouachita orogeny, and regional advective flow driven by stratigraphic controls, resulting in the hydrothermal fluid migration across the Midcontinent Paleozoic region. We will demonstrate the utility of coupling inverse modeling methods with hydrothermal fluid flow models to understand controls on the distribution of hydrocarbon reservoir quality. This research will significantly improve our ability to simulate regional fluid migration, and improve our understanding of the drivers, both structural and stratigraphic, of hydrothermal fluid flow.

Project Description

We will test two hypotheses:

H1) The topographic uplift associated with the Ouachita-Marathon deformation causing gravity-driven fluid flow through fractures was the dominant driver of fluid migration resulting in the record of repeated rises and falls in temperature associated with the Paleozoic Midcontinent region of the US (Figure 1).

H2) The regional stratigraphic and structural controls led to the character of the hydrothermal system, with a relatively normal geothermal gradient in the basin to the south transitioning northward into an inverse geothermal gradient with highest hydrothermal temperatures at the top of the Mississippian section (Figure 2).

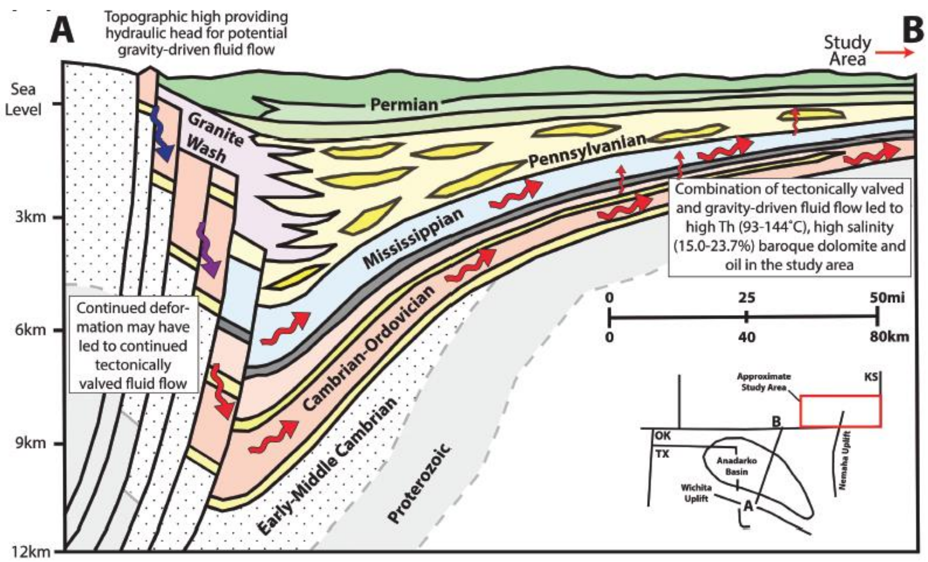

Figure 1: *Cross section schematic for topography-driven flow from uplift to basin and into the foreland. (Goldstein et al., 2019)*

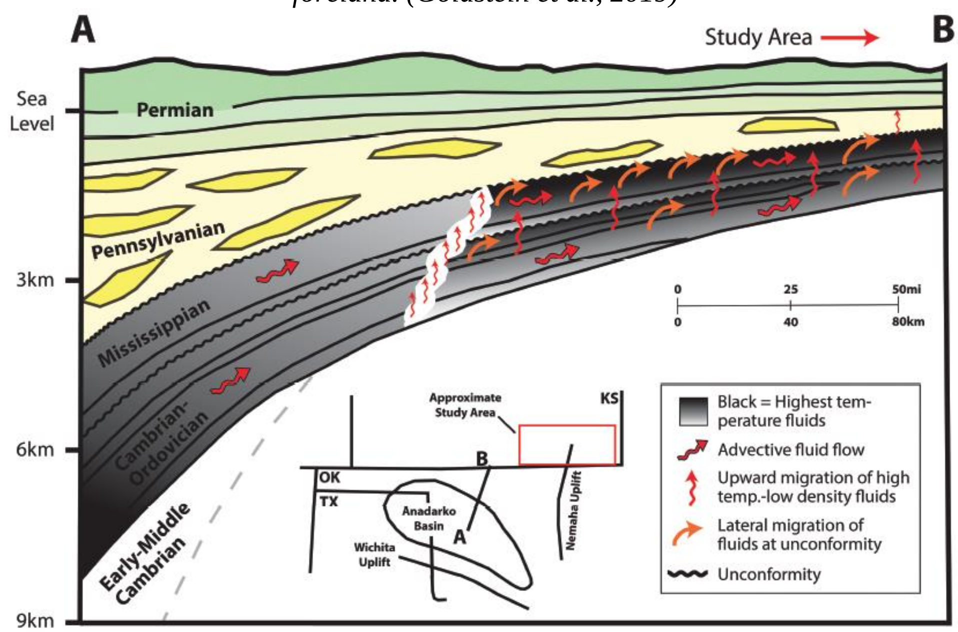

Figure 2: *Cross section schematic illustrating lateral transition from normal geothermal gradient to inverse geothermal gradient. The lateral transition between the two will be modeled with structure and stratigraphic control to evaluate which are feasible. (Goldstein et al., 2019)*

These hypotheses will be tested using an inverse modeling approach applied to a variable-density hydrothermal model of the Midcontinent Paleozoic region. We will use a coupled modeling framework, combining a parameter estimation and uncertainty analyses software package with a hydrologic model capable of capturing the processes and structures that control fluid flow and thermal transport in sedimentary basins (PEST-HydroGeoSphere [P-HGS]; e.g., Schilling et al., 2014). P-HGS couples the model-independent parameter estimation code PEST with HydroGeoSphere, a hydrologic model capable of variably saturated flow and transport in the subsurface, including fracture networks, density-driven flow, and thermal transport.

This research represents a novel approach to testing hypotheses related to fluid migration in the Paleozoic Midcontinent of the US. Previous modeling efforts have documented the difficulty related to calibration, uncertainty, and non-uniqueness in simulating this environment (e.g., Bethke, 1986; Appold and Garven, 1999; Chi and Xue, 2011). The proposed research will utilize parameter estimation and uncertainty software coupled with a hydrologic model to demonstrate the plausibility, and quantify the uncertainty, of both topographically driven fracture-enhanced fluid flow and stratigraphically controlled regional advective fluid flow in the Paleozoic Midcontinent region of the US.

Deliverables

Modeling results will provide a subset of scenarios and conditions that could lead to the hydrothermal record, giving insight into the plausibility of the proposed hypotheses. In addition, the uncertainty analyses can help guide future work, both observational and computational, by identifying what parameters contribute to the most model uncertainty, and what parameters have the highest data worth. This research will significantly improve our ability to simulate regional fluid migration, and improve our understanding of the drivers, both structural and stratigraphic, of hydrothermal fluid flow. The project will serve as a dissertation project for a student and results will be published and made available in the dissertation. Once constructed, the models can be modified by consortium members to simulate hydrothermal fluid flow in reservoir systems of interest to sponsors.

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Relative Abundance of Microporosity in Hugoton Limestones: Characterizing Low Permeability Pay in an Analog for Middle East Giant Fields

Franek Hasiuk, Sahar Mohammadi, and Robert Goldstein

SUBSURFACE APPLICATION: Basic research into microporosity in limestones; well-known in Arab, Kharaib, Mishrif, Shuaiba, Kangan, and Khuff Formations of the Middle East, Luconia platform, offshore Sarawak
STATUS: Awaiting funding
TIMING: Upon funding
FUNDING: Awaiting funding

Purpose

- To characterize the relative abundance of pore types in a supergiant gas field (Hugoton Field, Southwest Kansas)
- Test the hypothesis that microporosity forms below subaerial exposure surfaces under certain conditions
- Test the hypothesis that extant microporosity represents differential preservation after differential occlusion of micropores with cement
- Test the hypothesis that microporosity forms during shallow burial

Project Description

Natural gas forms a growing source of energy for electricity production in the United States for many utility companies, due to its lower carbon intensity. Production of gas from the supergiant Hugoton Field of southwest Kansas is expected to last only until 2050 and most of the remaining gas remains in low permeability strata (Dubois et al., 2006a). Some of this low permeability pay exists as microporosity in limestones, dolostones, and clastics (Figure 1; Dubois et al., 2006b). It has been argued that microporosity in Hugoton limestones forms from subaerial exposure (Olson et al., 1997), but recent work on the impact of subaerial exposure shows that the diagenetic alteration is highly dependent on climate, sequence architecture, duration of exposure, and hydrogeology, including the development of mixing zones (Figure 2; Buijs and Goldstein, 2012; Dubois et al, 2012). Recent research has shown that most microporosity in limestone petroleum reservoirs forms during shallow burial (Hasiuk et al., 2016).

Our long-term goal is to understand the paragenetic history of the Hugoton/Panhandle Field in Southwest Kansas, Oklahoma, and Texas as an integrated system. The objective of this proposal is first to characterize the relative abundance of pore types in the field as a method for understanding what pore types are contributing most to flow. Secondarily, we propose to test the hypothesis that: (1) microporosity in limestones forms during shallow burial and not during subaerial exposure. Alternatively, (2) if it is forming during subaerial exposure, we will test the hypotheses that it forms best during certain predictable conditions of (3) climate, (4) exposure duration, (5) hydrogeology, or (6) mixing. We will also test hypotheses that (7) extant distribution of microporosity is a function of differential preservation, with it forming early and differentially being occluded by later cements. We are well qualified to carry out this research due to our work on microporosity (Kaczmarek et al. 2015; Hasiuk et al., 2016), subaerial exposure and diagenesis in the Hugoton (Luczaj and Goldstein, 2000; Buijs and Goldstein, 2012; Dubois et al. 2012) and Permian-age supergiant gas fields (Mohammadi-Dehcheshmehi et al., 2013).

We will use cores from Hugoton with microporous limestone facies as identified in the Hugoton Asset Management Project (Dubois et al., 2006) that are closer to the Oklahoma border than those used in Buijs (2006). Analytical methods will build off the workflow from Buijs (2006). Standard petrographic methods will be used to build a paragenetic sequence for the macro and micro components of the reservoir. Geochemical methods (trace elements and stable isotopes), fluid inclusion data, and cold cathodoluminescence petrography will be used to further constrain paragenesis. Where calcite cements of high enough uranium content exist, U-Pb dating will be attempted to constrain the timing of diagenetic events. Scanning electron microscopy (SEM) will be used to look for evidence of "micro"-subaerial textures (e.g., micro-molds or micro-pendant cements). Electron dispersive spectroscopy on the SEM will be used to look for evidence of zonation in the calcite microcrystals hosting the microporosity. Routine core analysis (porosity and permeability) will quantify textural changes with petrophysical data.

Knowing whether microporosity is formed during burial or certain conditions of subaerial exposure will permit better geological models of reservoir properties to be constructed that will permit more accurate reservoir performance prediction. For example, if microporosity does form during subaerial exposure, it can be added to geological models below certain sequence boundaries. If not, it can be more broadly populated in a geological model by lithofacies.

Deliverables

- Workflow for integrating microporosity into geological models of supergiant gas fields
- Publications and presentations of research results
- Geochemical and fluid inclusion data, U-Pb age dates
- Core analysis data (helium porosity/permeability, mercury pore throat size distributions)
- SEM images of microcrystalline textures

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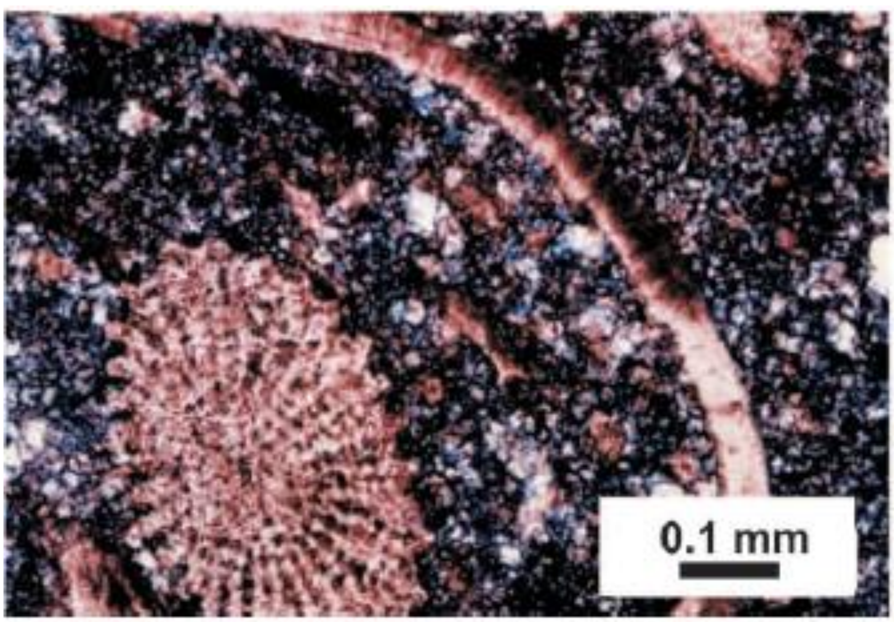

***Figure 1**. Photomicrograph of microporous wackestone from Hugoton field (Dubois et al., 2006a).*

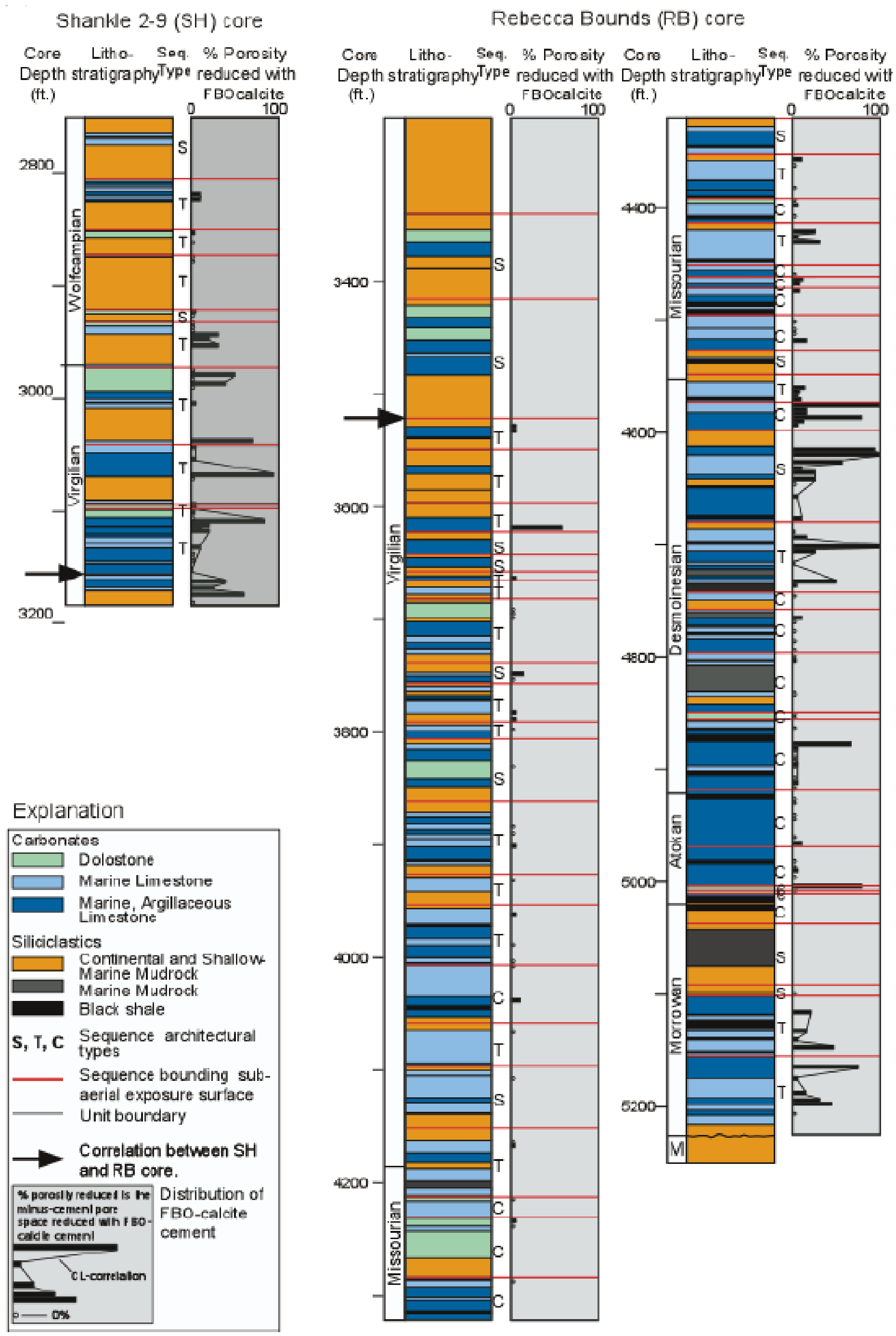

Figure 2. Stratigraphic record from two Hugoton cores illustrating differential response to multiple events of subaerial exposure, some of which result in precipitation of large amounts of meteoric and mixing-zone calcite cement (FBO) and some of which result in little cementation. (After Buijs and Goldstein, 2012)

Spatial Variability in Microporosity in a Carbonate Reservoir: Lansing-Kansas City Formation, Victory Field, Kansas

Franek Hasiuk (Kansas Geological Survey)

SUBSURFACE APPLICATION: Basic research into the diagenesis of microcrystalline calcite that hosts most microporosity in limestones
STATUS: Awaiting funding
TIMING: Upon funding
FUNDING: Awaiting funding

Purpose

- Understand how microporosity varies laterally in an oil reservoir to improve geological modeling

Project Description

Conventional carbonate petroleum reservoirs often suffer from low recovery efficiency on the order of 30 to 40%. This is caused in part from the heterogeneity of the pore systems that pervade carbonate reservoirs that are made up of interparticle, microporosity, touching vugs, and separate vugs (Lucia, 1995). Microporosity has been shown to be composed of micron-sized voids among micron-sized calcite crystals of various morphologies (Kaczmarek et al., 2015). These microcrystals have been suggested to be diagenetic cements that form during early burial (Hasiuk et al., 2016). What has not been shown, however, is how the textures of these crystals vary spatially in a reservoir and to what extent they are tied to lithofacies.

My long-term goal is to understand the origin and diagenesis of microporous carbonates. The objective of this proposal is to map the distribution of microcrystalline calcite textures in a carbonate reservoir (in both fine and coarse grained lithologies) from core samples. I am well qualified to carry out this research due to my previous work on microporosity (Kaczmarek et al. 2015; Hasiuk et al., 2016).

I will analyze the cores from the Lansing-Kansas City reservoir in Victory Field (Haskell County, Kansas; Figure 1) that have been interpreted to be microporous (Watney and French, 1988). The basis for this work will be mapping the relative abundance of pore types from core and petrographic thin sections. Scanning electron microscopy (SEM) will be used to characterize the morphologies of the calcite microcrystals and then these textures will be mapped spatially and compared to log response. Routine (porosity and permeability) and special core analysis (mercury intrusion capillary pressure) will provide quantitative data to correlate with the qualitative images of microcrystal morphology. Geochemical methods (elemental and stable isotopes) will also be used to characterize the diagenetic history of these limestones.

Knowing the spatial distribution of microporosity in a reservoir will permit better geological models of reservoir properties to be constructed that will permit more accurate reservoir performance prediction. For example, if microporosity is tied to certain parts of the skeletal sand shoals (e.g., shoal crests), this information can be used to more efficiently develop those facies.

Deliverables

- Workflow for mapping relative abundance of pore types (especially microporosity and microcrystalline calcite morphologies) across a carbonate reservoir
- Relative abundance of pore types from petrographic analysis
- Maps of microcrystal distribution by morphology
- Publications and presentations of research results
- Geochemical data
- Core analysis data (helium porosity/permeability, mercury pore throat size distributions)
- SEM images of microcrystalline textures

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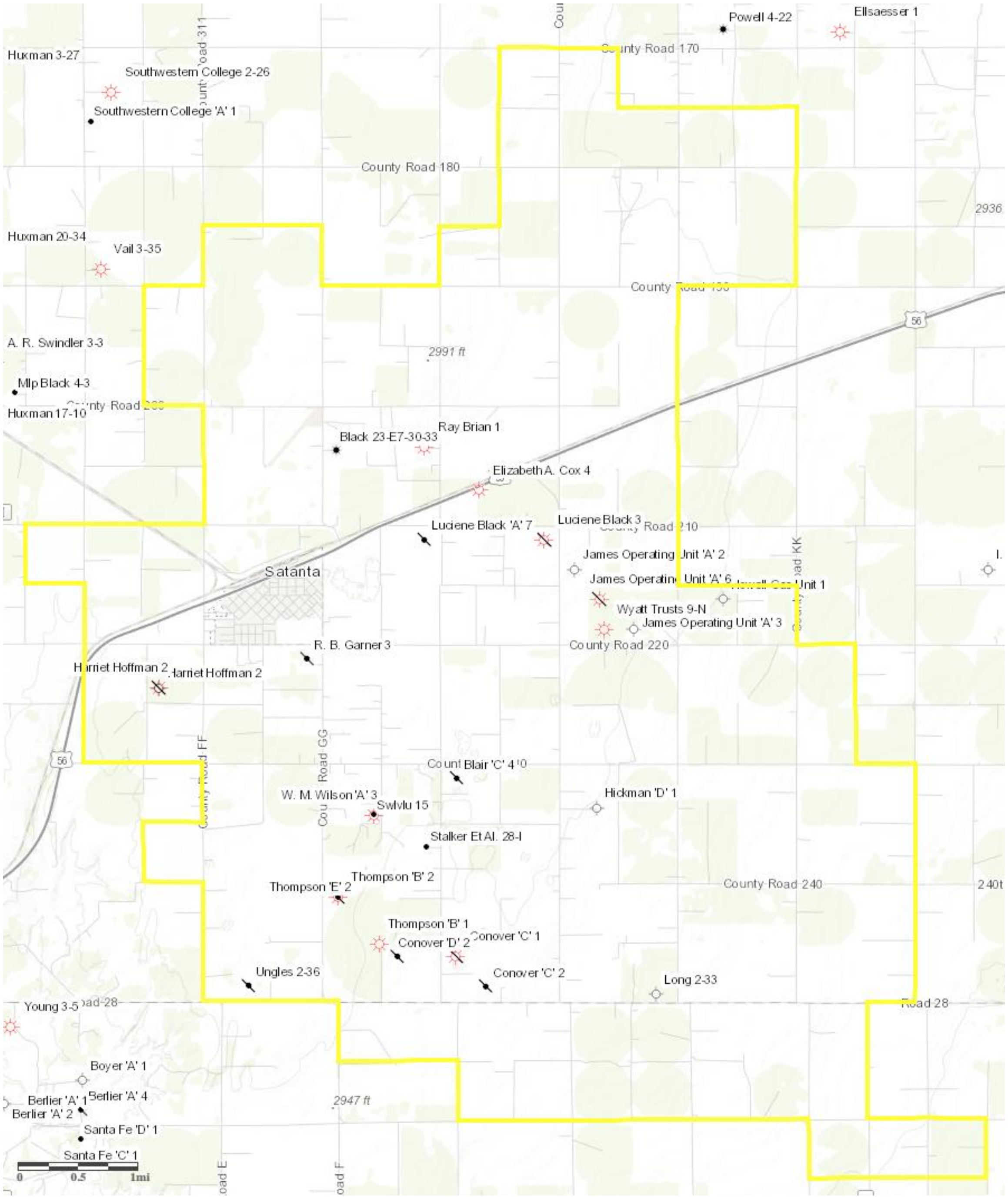

***Figure 1**. Victory Field map (yellow outline) showing locations of cores curated by KGS (map from KGS Oil and Gas field interactive web site).*

Chlorine and Bromine Isotopic Fractionation and Evolution During Evaporation

Randy Stotler and Robert Goldstein

SUBSURFACE APPLICATION: All reservoirs
STATUS: Proposed Project
TIMING: Upon Funding
FUNDING: None

Purpose

Evaporative environments, such as sabkha, and fluid-rock interactions with evaporative formations in the subsurface play an important role in the development of oil and gas reservoirs. As major ion components of oil-field brines and as a result of their generally conservative behavior, bromide and chloride compositions have long been used as environmental tracers of evaporation and fluid-rock interaction (e.g., Carpenter 1978; Davis et al. 1998; McCaffrey et al. 1987; Whittemore 2007). While the stable isotopes of chlorine ($^{37}Cl/^{35}Cl$) and bromine ($^{81}Br/^{79}Br$) are increasingly used to identify fluid evolution processes in a variety of environments, application of chlorine and bromine isotopes to investigations of evaporation and evaporites has not been as straightforward as hoped. Twenty years after the first study of fractionation of chlorine isotopes in evaporite minerals, the evolution of chlorine isotopes during evaporation remains controversial (Eastoe et al. 1999; Eastoe et al. 2007; Eggenkamp 2015; Eggenkamp et al. 2016; Eggenkamp et al. 1995; Luo et al. 2012; Luo et al. 2015; Luo et al. 2014). Similarly, early field results indicate bromine isotopic compositions of evaporites and evaporitic waters cannot be predicted from experimental results using binary solutions (Eggenkamp et al. 2016; Hanlon et al. 2017). This indicates that the basic understanding of the evaporative process provided by chemical composition alone is incomplete. *The goal of this study is to investigate chlorine and bromine isotopic evolution during evaporation of a variety of complex solutions through a series of laboratory experiments.* This will improve our understanding of the fate of chloride and bromide during evaporation and our ability to interpret fluid flow through subsurface reservoirs.

Project Description

To develop a more complete understanding of syn-depositional and post-depositional changes to evaporative environments and evaporite deposits, it is critical to understand the evolution of the chlorine and bromine isotopic compositions throughout evaporation. Briefly, a variety of simulated and natural waters will be evaporated to completion, where salinity, water chemistry, atmospheric and fluid temperatures, and atmospheric humidity are varied. Major and trace elements, and stable isotopes (H, O, Cl, Br) will be monitored throughout the experiments.

Deliverables

Specific deliverables include: 1.) Improved understanding of two critical indicators of fluid evolution and water-rock interaction; 2.) Fractionation factors for stable bromine isotopes during evaporation; and 3.) At least one manuscript.

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Characterizing the Isotopic Fingerprint of Formations and Fluids in the Mid-Continent

Randy Stotler and Robert Goldstein

SUBSURFACE APPLICATION: Mid-continent
STATUS: Proposed Project
TIMING: Upon Funding
FUNDING: None

Purpose

As a result of their generally conservative behavior, bromide and chloride compositions have long been used as environmental tracers of fluid evolution and cross-formational fluid flow (e.g., Carpenter 1978; Davis et al. 1998; McCaffrey et al. 1987; Whittemore 2007). With relatively advances in analytical capabilities for chlorine ($^{37}Cl/^{35}Cl$) and bromine ($^{81}Br/^{79}Br$) stable isotopic determination, more detailed interpretations of fluid evolution and cross-formational fluid flow are now possible. It is evident that application of these tools, in conjunction with oxygen ($^{18}O/^{16}O$) and hydrogen ($^{2}H/^{1}H$) stable isotope and strontium ($^{87}Sr/^{86}Sr$) isotopes can greatly improve understanding of a variety of questions relevant to reservoir exploration and development. Studies from the Williston Basin, Southern Ontario, Cherokee Basin, and Kangan (Iran) oil and gas producing regions have provided significant new insights (e.g., Bagheri et al. 2014a; Bagheri et al. 2014b; Shouakar-Stash 2008; Stotler, unpublished data; Stotler et al. 2017) including improved conceptual models for reservoir/saline fluid formation and evolution, and aquitard and wellbore seal integrity. The purpose of this project is to characterize the H, O, Cl, Br, and Sr isotopic fingerprint of the major oil and gas producing reservoirs and other formations of interest in the Mid-Continent.

Project Description

To develop an integrated understanding of fluid flow and evolution in a reservoir, it is critical to develop a library of the geochemical fingerprint of various units and fluids. Although we are interested in providing a deeper understanding of water-rock interaction and reservoir evolution across the entire Midcontinent, target basins and units will initially be chosen based on interest for KICC sponsors. Briefly, to develop the library, produced water samples will be obtained from operating wells, and will be analyzed for major and trace elements, and stable isotopic (H, O, Cl, Br, Sr) composition. Cl, Br, and Sr isotopic composition of geologic formations will be determined from archived core.

Deliverables

Specific deliverables include: 1.) Library of characteristic isotopic fingerprint for fluids and formations within the Midcontinent; and 2.) at least one manuscript.

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Effects of Seepage-Reflux Diagenesis on Porosity Modification in Carbonate Reservoirs

Robert H. Goldstein, David Fowle, and students

SUBSURFACE APPLICATION: Smackover reservoirs, Midcontinent Pennsylvanian, Mississippian, Arbuckle, Grayburg/San Andres, Wolfcamp, and Bone Spring of Permian Basin, Mississippian Williston Basin, Arab-D
STATUS: Long-term project in progress
TIMING: Significant results to be reported – Results currently available to membership
FUNDING: Partial

Purpose

Evaporative concentration of seawater at the surface leads to chemical evolution of the fluids, increased reactivity, and density inversion that leads to sinking of brines downward through less dense fluids. The process, which was originally introduced as seepage-reflux, a mechanism of dolomitization proposed by Adams and Rhodes (1960), is now known as a widespread process with major effects on oil and gas reservoir rocks. ***The purpose of this research is to systematically evaluate the effects and distribution of refluxing systems in carbonate reservoir rocks, as a means for predicting porosity distribution.***

Project Description

For many years, reflux was one of those undersubscribed diagenetic processes. It is now known that very little evaporative concentration is required to have refluxing fluids penetrate deeply into carbonate platforms. Now, we know that reflux is common, a major diagenetic process, and that it requires very little evaporation. It leads to dolomitization, anhydrite precipitation, and calcite cementation. This process has had a major effect on many large and small carbonate reservoirs around the world.

On the Great Bahama Bank, for example, it is well known that during certain times of the year, salinity becomes slightly elevated above that of normal seawater (Traverse and Ginsburg, 1966). Reflux of this bank water is taking place today, and has taken place in the past. In their study of karst of the eastern part of the bank, Whitaker and Smart (1990) demonstrated that saline waters of the lagoon sink to depths of about 150 m and discharge eastward into the Tongue of the Ocean. In the subsurface from 60 to 1100 m depth, west of the bank margin, salinity is high (up to 62 ppt; Kramer et al., 2000). Calcite cement from the Pliocene section of the Clino core contains saline fluid inclusions indicating an origin from reflux (Goldstein et al., 1998). It is interpreted that refluxing fluids dolomitized sediment updip leading to calcite cementation downdip.

Some of the dolomite from deep core of Enewetak Atoll is best explained by deeply sinking moderate salinity refluxing brines (Goldstein, 1996). Enewetak consists of 1400 m of carbonate overlying volcanic basement. Two cores have been taken and sample all the way down to basement. There is porous dolomite near the base of the section that owes its origin to deeply refluxing, relatively recent fluids, on the basis of dolomite Sr isotopic compositions, oxygen isotopic compositions, and fluid inclusions ranging from 44-85 ppt.

If surface waters on a carbonate platform reach high salinities, initially, it is expected that refluxing brines would dolomitize the host sediment. Downdip, however, reactive transport models suggest that anhydrite should precipitate and plug significant amounts of pore space (Jones and Xiao, 2005). This process appears to be an excellent explanation for early anhydrite plugging in some systems. In repeated examples of ancient systems, however, reflux appears to result in updip dolomitization and downdip calcite cementation, which exerts major controls on reservoir porosity. In the Permian and Pennsylvanian rocks of western Kansas, for example, brine reflux led to dolomite reservoirs close to the source of refluxing brines (Luczaj and Goldstein, 2000), but down section, about half of the reservoir porosity was occluded by the same brines farther along their flow path (Goldstein et al., 1991). This process, resulting from reflux, dolomitization, and microbial sulfate reduction, appears to be among the most important diagenetic processes in large-scale reduction of porosity by calcite cementation.

The project proposes to systematically examine regionally extensive reflux systems from the surface and subsurface. It will reconstruct the flow path using cathodoluminescence cement stratigraphy, stable isotope geochemistry, and fluid inclusion microthermometry. These data will be used to calibrate reactive transport models for diagenetic alteration of carbonate systems.

Deliverables

This project will provide quantitative data on the effect of reflux processes on carbonate reservoir rocks. It will concentrate first on developing conceptual models for porosity modification, such as top-down and bottom-up patterns related to fluid flow. It will provide ground truth for manipulation of reactive transport models to quantitatively predict distribution of dolomite, anhydrite, and calcite cement related to this process.

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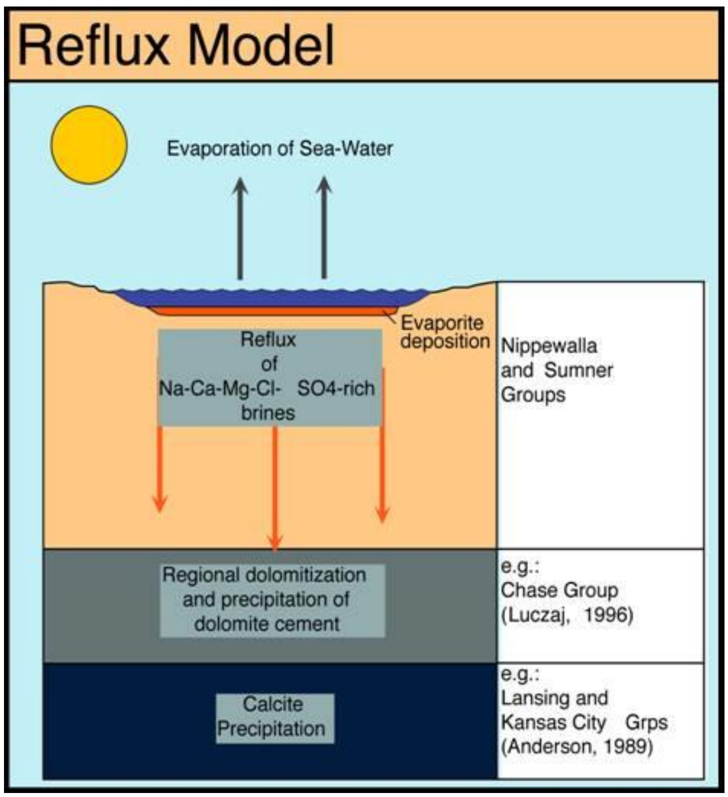

Figure 1. *Regional fluid flow model for dolomitization and calcite cementation in Permian and Pennsylvanian reservoirs, Kansas.*

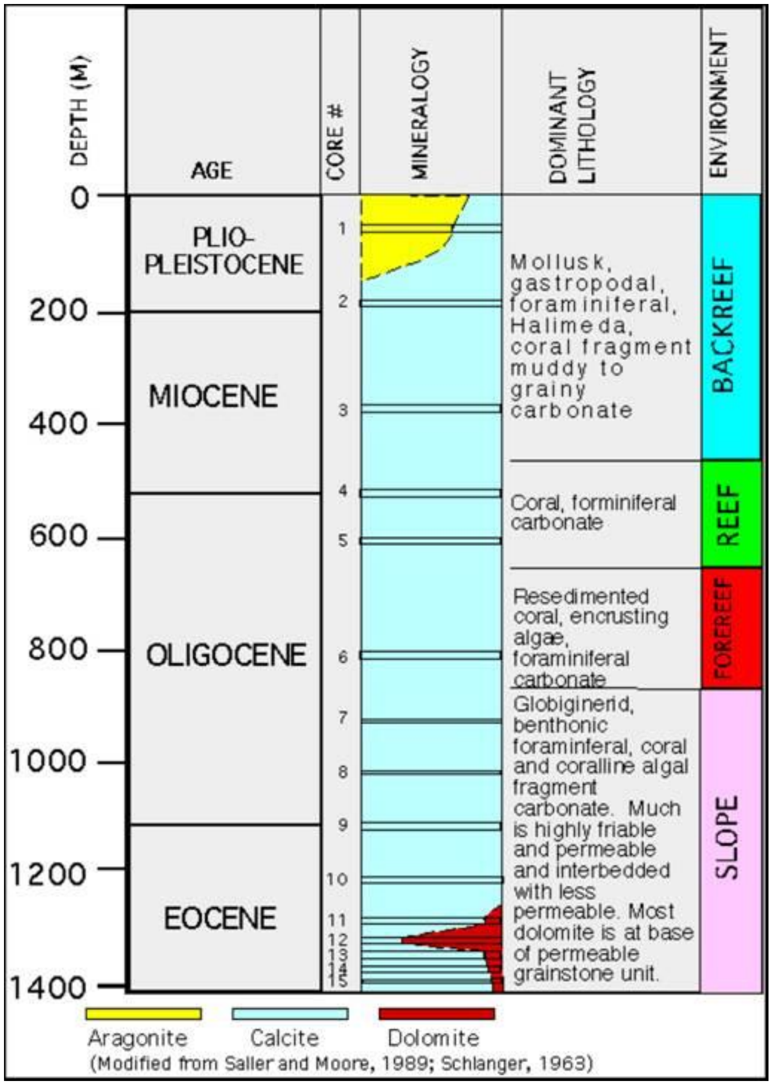

Figure 2. *Example of bottom-up diagenetic pattern of dolomitization related to flow of dense fluids along base of aquifer system.*

Superhighways for Hydrothermal Fluid Flow in the Midcontinent: Structural and Stratigraphic Controls on Thermal Structure, Flow Rate, and Reservoir Properties

Robert H. Goldstein, Hassan A. Eltom, Sahar Mohammadi, Lynn Watney, Tandis Bidgoli.

SUBSURFACE APPLICATION: Ghawar Field, North Field, Ladyfern, presalt Brazil/Angola, Mississippian Lincoln County Colorado, Albion-Scipio, Tengiz, Trenton-Black-River, Arbuckle/Ellenberger and Pennsylvanian Permian Basin and Midcontinent, Mississippian Lime in Kansas, Woodford Chert of the southern USA midcontinent, Shale plays of the Permian Basin, and Bakken/Lower Lodgepole play
STATUS: Beginning stages of project
TIMING: Preliminary results available; project underway
FUNDING: Partial from DOE

Purpose

This project proposes to improve understanding of the effects of hydrothermal fluid flow in regionally advective and fault-pumped systems. This will be accomplished by integrating data from a regional case study from the Midcontinent of North America to be followed by coupled flow and thermal modeling. The workflow for modeling will be tested by using the rock record of a well-studied example that shows density controls on hydrothermal fluid flow leading to predictable alteration with a stratigraphic and structural control. Data on diagenetic alteration and fluid flow will be compared to rock properties and reservoir performance, to evaluate the control of coupling of fluid and structural/stratigraphic setting on localization of the best reservoirs.

Project Description

In many conventional and unconventional carbonate reservoirs, there is strong evidence that hydrothermal fluid flow has had an impact on reservoir quality (Davies and Smith, 2006). Hydrothermal systems require flow of warm fluids into cooler rocks to affect the thermal regime. Hydrothermal porosity enhancement has been incorrectly ascribed to meteoric diagenesis in many cases. For example, in the Midcontinent of North America, it has been suggested that meteoric dissolution associated with unconformities led to much of the reservoir porosity in Midcontinent carbonate reservoirs (*e.g.* Duren 1960; Euwer 1965; Thomas 1982; Rogers *et al.* 1995; Montgomery *et al.* 1998; Franseen, 2000; Watney *et al.* 2001; Franseen *et al.* 2004; Mazzullo *et al.* 2009). New data show that late hydrothermal fluid flow in Ordovician, Mississippian, and Pennsylvanian reservoir rocks of the Midcontinent have had a major impact on porosity in conventional high-permeability reservoirs as well as low-permeability unconventional reservoirs (Goldstein and King, 2014; Ramaker *et al*. 2014). These fluids also have had an impact on hydrocarbon migration and local thermal maturation in these systems. Although recent publications have challenged the impact of porosity generation at high-diagenetic temperatures in hydrocarbon reservoirs (Ehrenberg *et al.* 2012), the small Midcontinent reservoirs have clearly been affected. Moreover, this effect is unequivocal at the other end of the size spectrum, including the largest hydrocarbon reservoir in the world, Ghawar (Cantrell et al, 2004). Thus, understanding the controls, and impact on hydrothermal alteration is of broad import for the oil and gas industry.

The Midcontinent USA is ideal to develop the geologic constraints necessary to improve our ability to develop general modeling approaches applicable to various subsurface

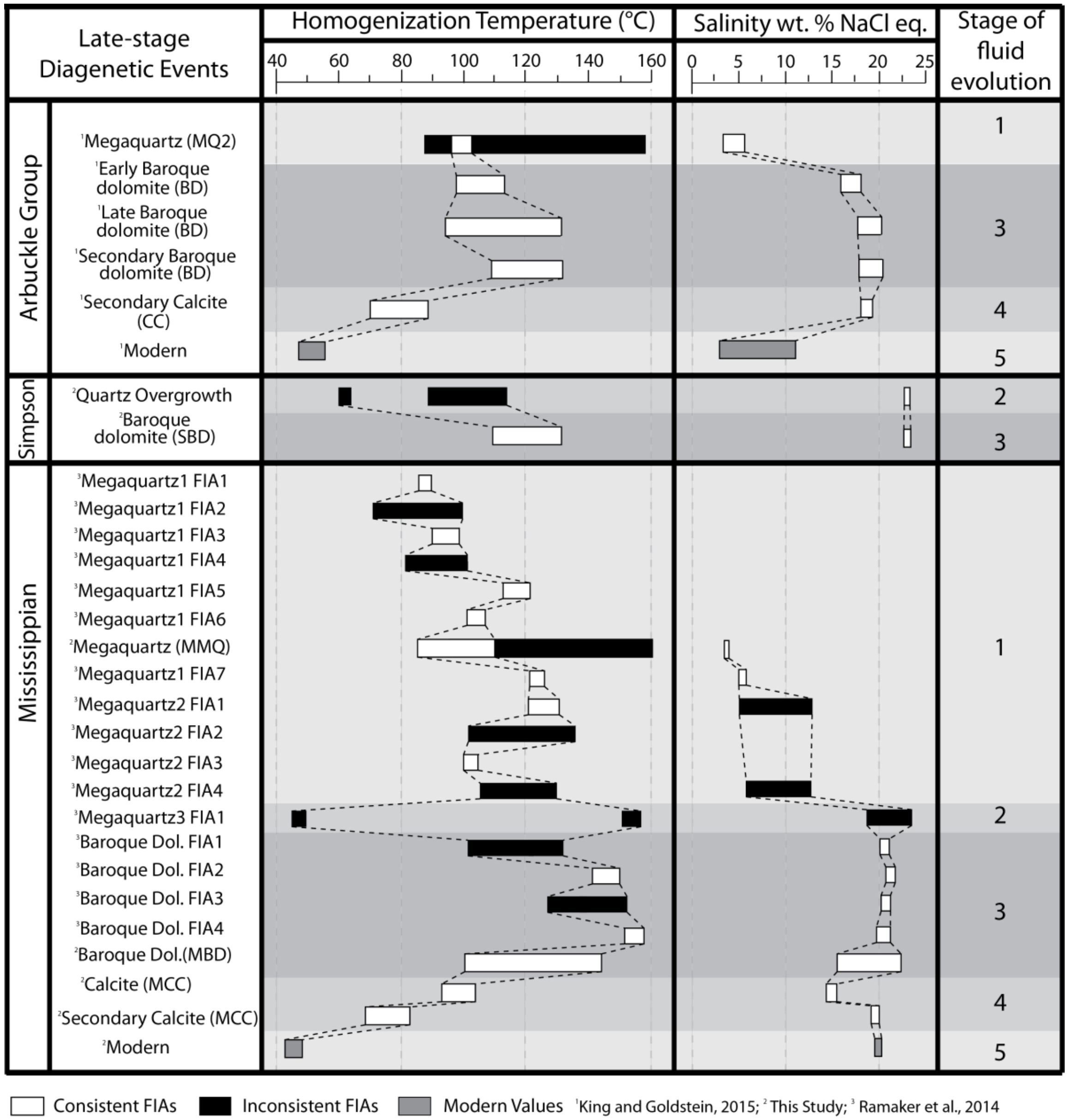

Figure 1. *Summary of fluid inclusion homogenization temperatures and salinities from the Midcontinent.*

systems. The hydrothermal fluid flow in the USA Midcontinent occurred in three late stages (King, 2013). Fluid flow was controlled by stratigraphic discontinuities, fault and fracture systems, and temperature-controlled density differences, and had an impact on thermal maturation, porosity, and hydrocarbon migration.

Work to date demonstrates how stratigraphic discontinuities associated with unconformities control later hydrothermal fluid flow to create the superficial appearance that porosity originates during low-temperature meteoric diagenesis. It develops a regional data set from reservoirs, shallow cores, and outcrops from the Midcontinent, USA and integrates regional stratigraphic data from the Ordovician through the Pennsylvanian, petrography, fluid inclusions, and stable isotopes to demonstrate the evolution of the hydrothermal system. Petrographic data show that the entire region and stratigraphic succession experienced a similar late time-equivalent paragenesis - with megaquartz, silica dissolution, carbonate dissolution, baroque dolomite, ore minerals, and calcite. Fluid inclusion data in the megaquartz, baroque dolomite, and calcite confirm a complex record of hydrothermal fluid flow, beginning with migration of low salinity connate fluids and gas, and evolving to migration of concentrated brines and oil (Fig. 1).

During the second phase of hydrothermal alteration, integrated data indicate advective fluid flow from the basin to the South. A regional dataset shows the Ordovician through Mississippian section was hydrologically connected and that the shale-rich Pennsylvanian section acted as a leaky confining unit (Fig. 2). Temperatures increased upward in the Ordovician-Mississippian section and were lower and decrease upward in the Pennsylvanian section. The data indicate vertical hydrologic connections that allow the warmest, lowest density fluids to float toward the top of the hydrothermal aquifer, concentrating dissolution from hydrothermal solutions below the Mississippian-Pennsylvanian unconformity.

Later, the system evolved from a regionally advective hydrothermal system to a fracture-controlled system. After or during fracturing, hydrothermal solutions precipitated calcite and showed regional geochemical trends indicating vertical fluid flow along fractures, directly from basement or a basal sandstone aquifer (Fig. 3). This late system shows no stratigraphic control and is likely driven by highly localized fault pumping of the hydrothermal fluids.

For the reservoirs studied, the most important system for porosity modification was the regionally advective hydrothermal aquifer, which had warmer fluids at its top, coincident with a stratigraphic discontinuity/unconformity. Porosity enhancement immediately below the unconformity can be ascribed to hydrothermal fluids, which leads to a significantly different model for exploration for the best reservoir quality. This type of fluid flow differs greatly from the highly localized fluid flow interpreted for Trenton-Black River hydrothermal dolomite reservoirs (Davies and Smith, 2006).

This study will focus on developing an improved understanding of predictability of hydrothermal alteration associated with regionally advective hydrothermal flow.

- All Midcontinent reservoir and nonreservoir carbonate diagenetic data (geochemical) and thermal alteration data will be synthesized to develop an improved picture of spatial and stratigraphic impacts of hydrothermal alteration.
- The spatial distribution of these data will be correlated to oil field data (locations of producing wells, water cuts, production history, reservoir quality) and seismic data (provided by consortium members) to improve exploration tools for hydrothermal reservoir enhancement.

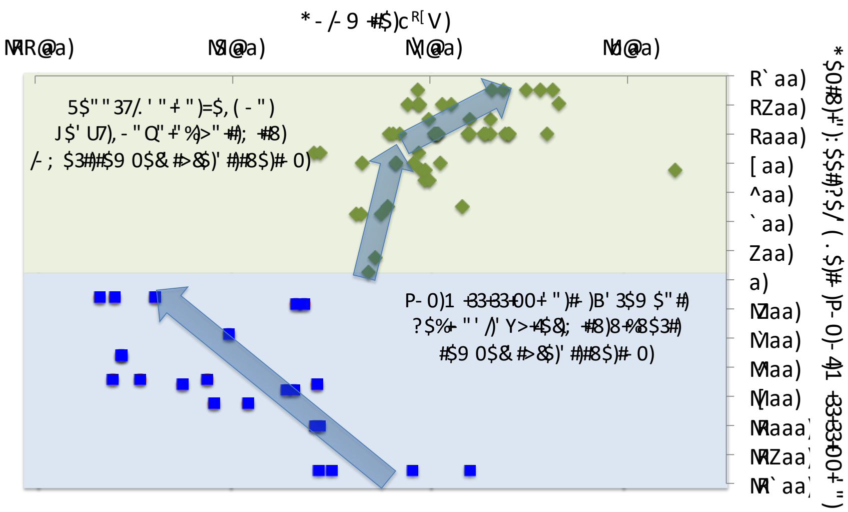

Figure 2*. Oxygen isotopic data from baroque dolomite showing evidence for hydrothermal dolomite temperatures increasing upward in the Ordovician-Mississippian section. Lower temperatures are in the Pennsylvanian confining unit.*

- Thermal history and porosity evolution will be compared spatially to restraining bends on faults, flower structures, and fault orientation to develop predictive models for superhighways for hydrothermal fluid flow, porosity enhancement, oil migration, and thermal maturation of organic matter (Fig. 4)

Deliverables

The project will explore an important type of hydrothermal alteration in which fluid flow and porosity enhancement had a stratigraphic control. This differs greatly from a common perception of fault pumping as the only applicable model.

The full data set of Midcontinent diagenetic and thermal alteration will be provided as an integrated report focusing on the Ordovician through Pennsylvanian section. This will provide the basis for testing hypotheses of the parameters controlling hydrothermal alteration.

When these data are compared to oil field data, the project will provide a set of conceptual models for reservoir sweet spots in such a system. When they are compared to seismic data, the results will provide seismic signatures that aid in exploration for hydrothermal alteration and porosity enhancement.

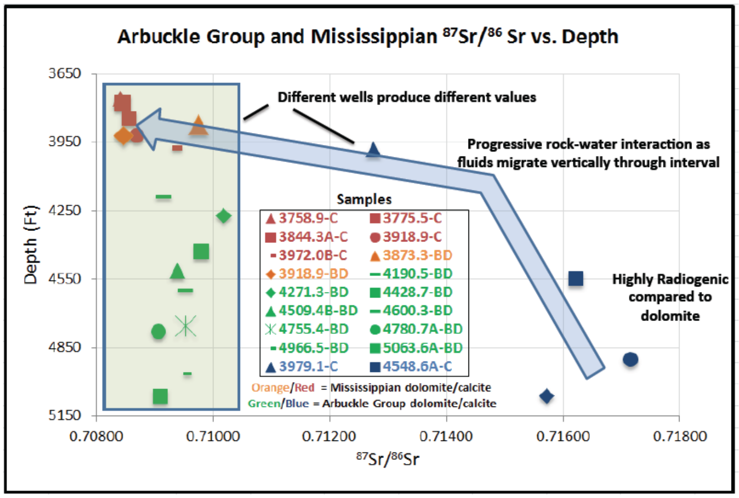

Figure 3. *Sr isotope data from Stage 3 calcite and Stage 2 baroque dolomite. Baroque dolomite shows values similar to host rock, indicating long distance advective fluid transport and extensive rock-water interaction. Calcite data indicate progressive rock-water interaction from base to top and well-to-well variation suggestive of vertical fluid flow along localized faults and fractures.*

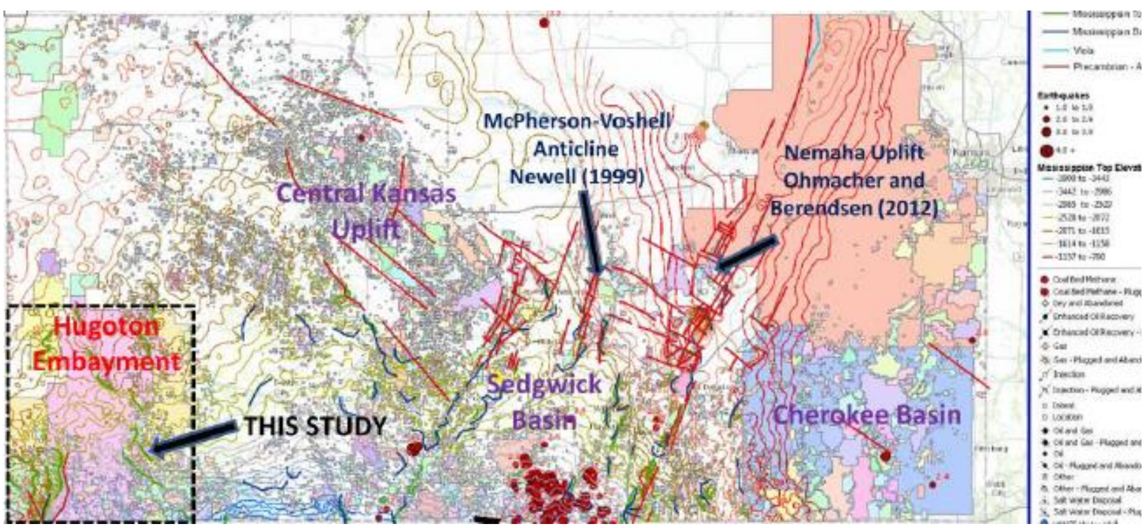

Figure 4. *Structural contour map on the top of the Mississippian in Kansas with documented and inferred faults. (after Hedke and Watney, 2016)*

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Quantifying Processes of Diagenetic Alteration in Mixing Zones: Cementation, Dissolution, and Dolomitization in Special Settings

Robert H. Goldstein, ExxonMobil team, Anita Csoma, and Zhaoqi Li

SUBSURFACE APPLICATION: Important for all carbonate reservoirs that have experienced subaerial exposure such as Tengiz, Arbuckle/Ellenburger/Tarim, Pennsylvanian/Permian of Permian Basin and Midcontinent, Mississippian Midcontinent, Shuaiba, Lisburne Group of Alaska
STATUS: Long-term project in progress
TIMING: Significant results to be reported – Results currently available to membership
FUNDING: Partial

Purpose

In the context of carbonate diagenesis, mixing zones commonly describe groundwaters that are mixtures between seawater and freshwater, and thus have compositions intermediate between the two. ***The goal of this project is to systematically evaluate the effect of mixing ratio and end-member fluid composition on diagenetic processes in mixing zones to evaluate the effects on porosity in carbonate systems***.

Project Description

Given mixing of seawater and meteoric waters, in the past, most researchers would call on dolomitization and perhaps dissolution in carbonates (Runnels, 1969; Badiozamani, 1972; Land, 1972; Plummer, 1975). Researchers would expect that mixing ratio would be the primary control on the diagenetic product, as that is supported by thermodynamics. Many recent studies of mixing zones, however, fail to show dolomite, or the interpretation of the dolomite's origin is debated (e.g., Csoma et al., 2006; Figure 1). On the contrary, mixing zones seem to produce a wide variety of cement mineralogies from low-Mg calcite, to high-Mg calcite, to aragonite, and dissolution (Frank and Lohmann, 1995; Melim et al., 2004; Csoma et al., 2004). Moreover, fluid inclusion data show no predictable control of mixing ratio on mineralogy of precipitate or dissolution (Csoma et al., 2006). It appears that dynamic processes, such as outgassing at the water table and microbial activity, may dominate predictability in these systems, and this interpretation calls for geochemists to take a new approach toward modeling such systems.

Moreover, the state of the end member saline fluid may exert a significant effect. It is known that there have been times when tropical surface seawater was precipitating aragonite and high-Mg calcite, as it does today; but it is also well known that at other times, dominant mineralogies of tropical seawater precipitates were calcite (Sandberg, 1983). During some of those times, it appeared that aragonite in tropical surface seawater dissolved right on or just below the seafloor (Johnson and Goldstein, 1993; Wright and Cherns, 2007). Some reasons for these shifts have been changes in atmospheric pCO_2 and marine Mg/Ca over time (e.g., Demicco et al., 2005; Berner and Kothavala, 2001), demonstrating that modern seawater may not be the best model for ancient seawater.

This project concentrates on fluid inclusion and stable isotopic analysis of purported mixing zone diagenetic phases to characterize processes and products through time and in various hydrologic settings. It evaluates the effect of mixing ratio, proximity to water table, hydrogeology of the system, and composition of saline end member as controls on processes and products in mixing zones.

Deliverables

Recent results have indicated that the mixing zone dolomite model is not dead, as suspected by many. The research already has provided quantitative data on dolomite distribution by this (Figure 2) process and discovered a new hydrologic mechanism controlling dolomitization called ascending freshwater-mesohaline mixing (Figure 3). This type of dolomitization by ascending mixing leads to porosity enhancement (Figure 4). All other mixing zones appear to lead to cementation and dissolution depending on proximity to water table, and microbial activity. Mixing ratio is less important than originally proposed on diagenetic product.

Deliverables will be a series of case studies in various settings. These projects define the parameters that are needed to be modeled for quantitative prediction of mixing zone systems in reactive transport models. Reactive transport modeling will be applied to evaluate parameters useful in predicting dolomitization by ascending freshwater-mesohaline mixing

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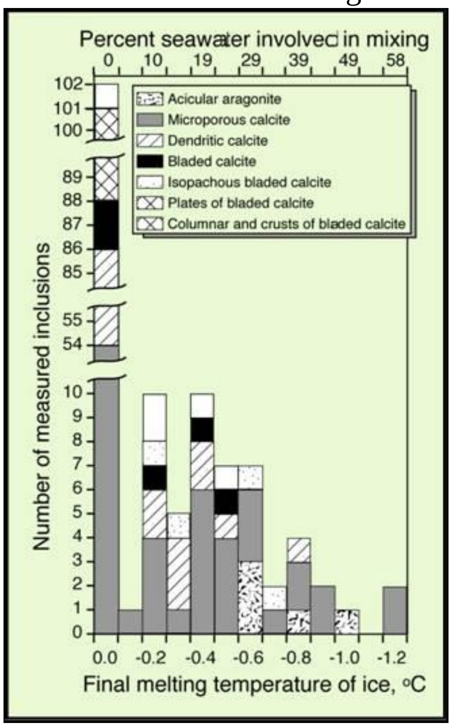

Figure 1. Fluid inclusion data (from Csoma et al. 2006) illustrating that water table dynamics appear to be a more important control on diagenetic process than mixing ratio.

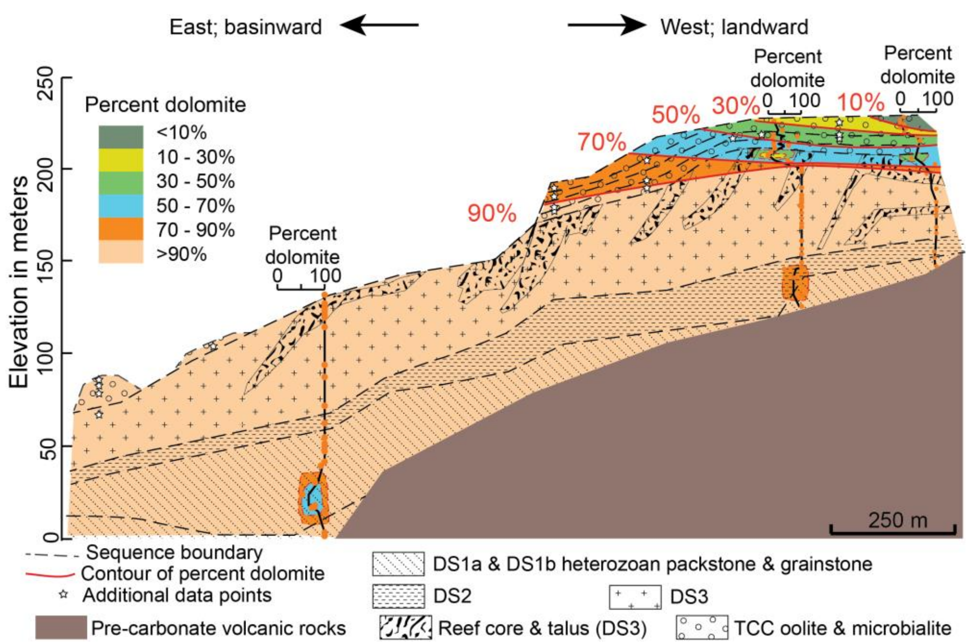

Figure 2. *Cross section of La Molata Platform with contours of percent dolomite superimposed to illustrate the distribution of dolomite. Dolomite abundance increases basinward and stratigraphically downward. In general, this carbonate platform has been extensively dolomitized. The rocks of greater than 90% dolomite comprise at least 80% of this platform (Li et al., 2013)*

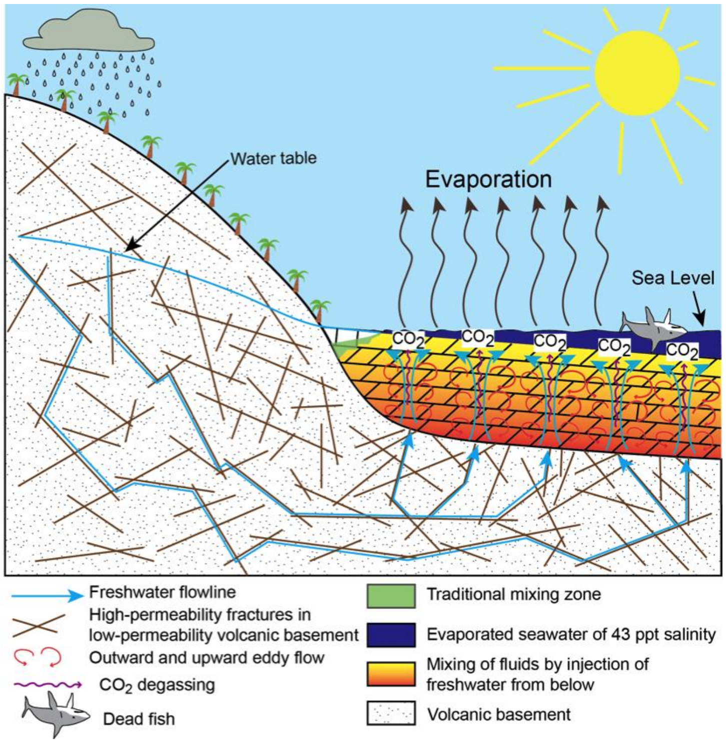

Figure 3. *Dolomitization from ascending freshwater-mesohaline mixing. Fractures in the volcanic rocks provide fluid pathways for freshwater flux. Hydraulic head from hinterland and density contrast force freshwater upward when discharging into carbonate platform. This createsextensive fluid mixing. Upward flow of fluids leads to decrease of pressure, which results in degassing of* CO_2*. Fluid mixing of freshwater and mesohaline seawater, and degassing of* CO_2 *may all be responsible for extensive dolomitization (modified from Li et al. 2013).*

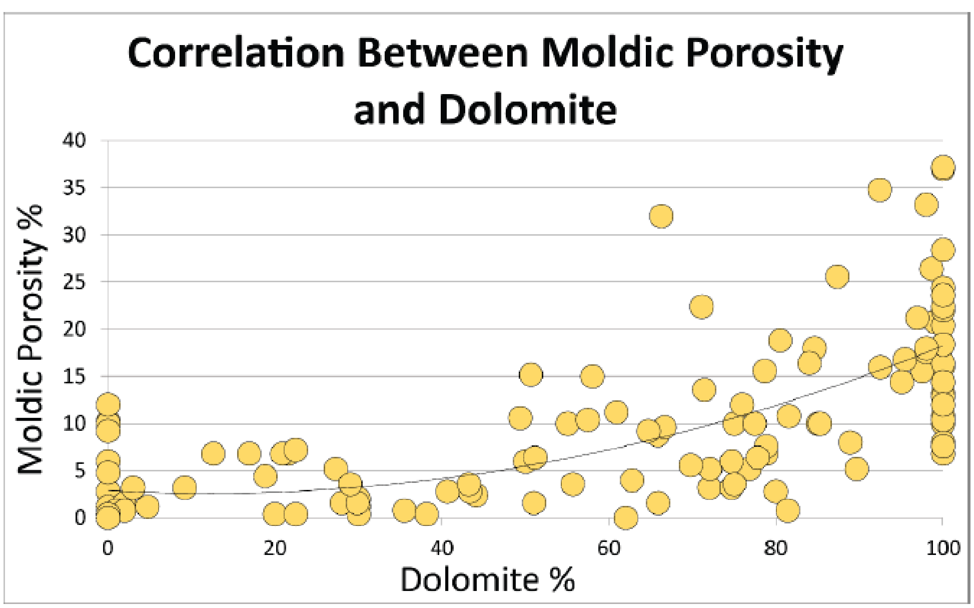

Figure 4. *Correlation between dolomitization from ascending mixing and enhancement of moldic porosity (thesis by Tony Pugliano).*

Modification of Reservoir Porosity by Hydrothermal Fluids: Recognition and Setting

Robert H. Goldstein and students

SUBSURFACE APPLICATION: Ghawar Field, North Field, Devonian of Western Canada, presalt Brazil/Angola, Mississippian Lincoln County Colorado, Albion-Scipio, Tengiz, Trenton-Black-River, Arbuckle/Ellenberger and Pennsylvanian Permian Basin and Midcontinent, Mississippian Lime in Kansas, Woodford Chert of the southern USA midcontinent, Shale plays of the Permian Basin, and Bakken/Lower Lodgepole play
STATUS: Long-term project in progress
TIMING: Significant results to be reported – Results currently available to membership
FUNDING: Partial

Purpose

It is now well known that warm fluids injected into cooler rocks have an effect on thermal maturation and porosity distribution. In some cases, such hydrothermal systems enhance porosity and in others they reduce it. *The goal of this long-term project is to develop techniques for recognition of hydrothermal systems, and evaluate how geologic setting controls porosity modification to begin to form predictive conceptual models useful in the oil and gas industry*.

Project Description

Carbonate specialists are just now identifying the hallmarks of hydrothermal processes (e.g., Smith and Davies, 2006) and recognizing that many pore systems thought to have formed by meteoric waters were likely to have formed from hydrothermal fluids (Esteban and Taberner, 2007). Some of the largest oil (e.g., Ghawar) and gas (e.g., North) fields have been affected by hydrothermal alteration. Hydrothermal processes in reservoirs are known to lead to moldic porosity (e.g., Newell et al., 2003), cavernous pores (Carlson, 1995), vugs (Hiemstra and Goldstein, 2005) and solution enlargement of fractures. Ultimately, the explanation for hydrothermal porosity enhancement may simply be the cooling of hydrothermal fluids, which leads to undersaturation with respect to carbonate minerals (Rossi et al., 2002), but mixing and other processes are possible (Mazzullo and Harris, 1991; Salas et al., 2007).

To understand many hydrothermally enhanced reservoirs, it appears necessary to understand early as well as late paragenesis. For example, using data from the Indian Basin Field, New Mexico, Hiemstra and Goldstein (2005) showed that the distribution of hydrothermal dolomite and secondary porosity were controlled by depositional setting, preferentially forming where facies were deposited deep enough to escape early meteoric diagenesis, as well as proximity to fault and fracture systems in the presence of a fluid drive (Figure 1). This complex group of controls led to the best reservoirs forming only in downdip positions, and would not have been predictable without understanding the earlier paragenesis.

This project will systematically study reservoir carbonates and use fluid inclusion and other geothermometers to develop methodologies for the identification of ancient hydrothermal systems. Models for fluid flow will be developed for implementation of predictive models based on geologic setting.

Deliverables

Hydrothermal alteration is clearly important in the localization of sandstone and carbonate oil and gas reservoirs as well as MVT ore deposits (e.g. Leach and Sangster, 1993; Wojcik et al., 1997; Rossi et al., 2002; Cantrell et al., 2004; Smith and Davies, 2006; Davies and Smith, 2006). Fluid inclusions and other geothermometers are essential in recognizing ancient hydrothermal fluid flow. Geothermometers, such as fluid inclusions, are useful in identifying when and where the normal burial system has been perturbed by hydrothermal fluid flow and flow of cool waters into warmer rocks.

New results show that hydrothermal systems typically require a mechanism to move fluids upward from deeper parts of the basin, a setting in which warmer fluids exist and are capable of being transmitted into cooler rocks, and conduits such as fractures or permeable horizons that provide a focus for rapid fluid flow.

There has been much discussion of the criteria necessary to identify ancient hydrothermal heating (e.g., Machel and Lonnee, 2002; Esteban and Taberner, 2003; Davies and Smith, 2006). It has been suggested that measured paleotemperature higher than predicted from burial history modeling is an appropriate indication. On the other hand, it must be pointed out that the many assumptions of such modeling and the nature of the thermal maturity data typically available (i.e., vitrinite reflectance, pyrolysis data from Rockeval) normally make it impossible to unequivocally distinguish between a hydrothermal system, higher heat flow than modeled, or deeper burial than interpreted.

New models, developed in this research, for identification of hydrothermal systems include evidence for: (1) fluctuating paleotemperature; (2) geothermometers higher than possible from burial history models; (3) gradients and pressure data inconsistent with normal thermal regime; (4) variation in paleotemperature at same depth; and (5) higher paleotemperatures in conduits (Figure 2).

Detailed case histories of hydrothermal alteration will be used to constrain geologic models of localization of porosity enhancement and reduction.

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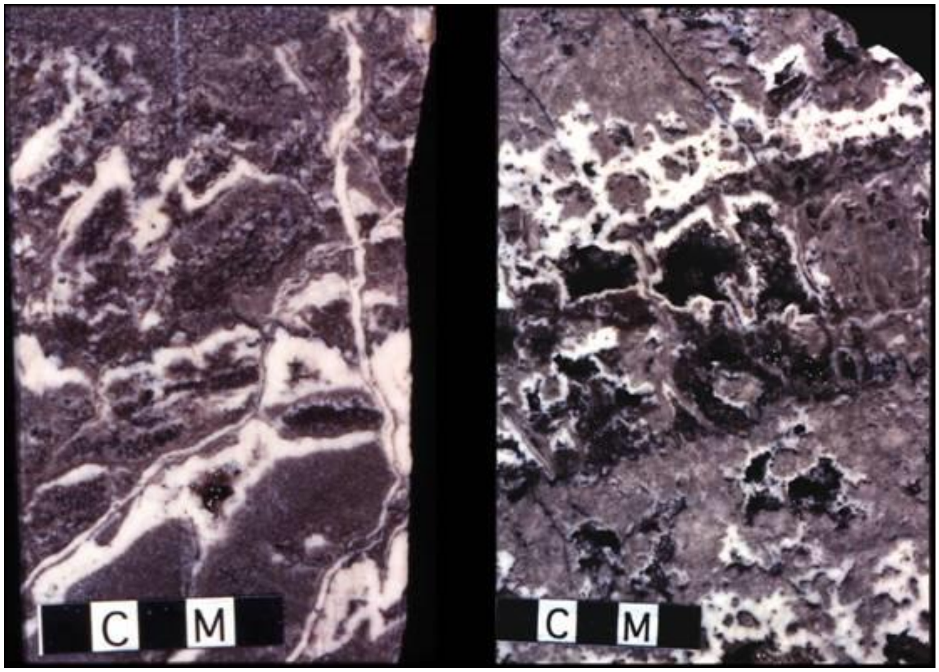

Figure 1. *Core images from the Indian Basin field, studied by Erik Hiemstra. Hydrothermal processes have both enhanced and reduced porosity.*

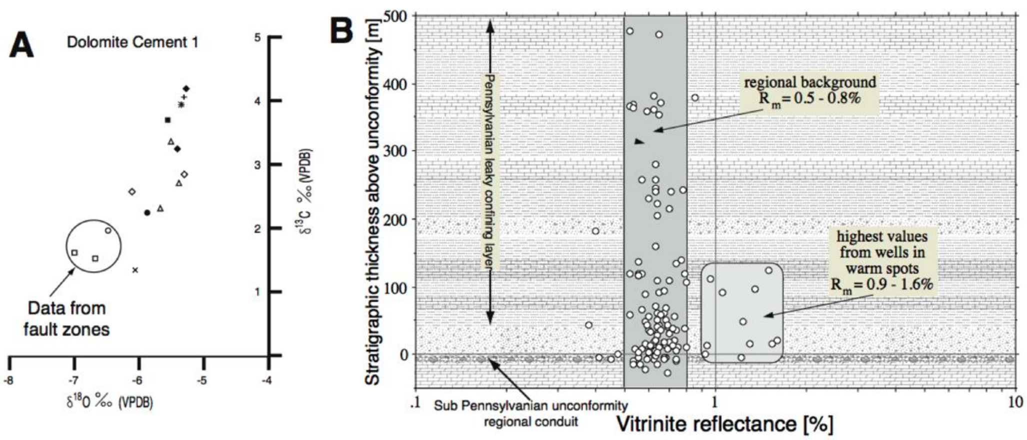

Figure 2. *A. Carbon and Oxygen stable isotope data from Indian Basin field of New Mexico. Data come from dolomite cement, correlated with cement stratigraphy and shown to be approximately time equivalent throughout the area. Circled data are from fault zones and other data come from the same dolomite phase away from fault zones. The more negative oxygen isotopic data indicate that the dolomite from the fault zones formed from warmer fluids than the dolomite outside of the fault zones. This character confirms a hydrothermal origin in which the fault zones were preferred conduits for fluid flow (Hiemstra and Goldstein, 2005) B. Stratigraphic variation in vitrinite reflectance values from Pennsylvanian strata of southeastern Kansas. Locally, anomalously high vitrinite values are located in close stratigraphic proximity to the sub-Pennsylvanian unconformity. The diagram shows schematically that the sub-Pennsylvanian unconformity is a regional paleokarst, and that it acts as a regional stratigraphic conduit for hydrothermal fluid flow. The Pennsylvanian section, however, acts as a leaky confining unit. This pattern confirms hydrothermal fluid flow for the system. Data from Barker et al. (1992). Modified from Walton et al. (1995).*

Experimental Approaches to Primary Low-Temperature Dolomite Formation in Carbonate and Mixed-Siliciclastic Systems

Jennifer Roberts, Luis González, Randy Stotler

SUBSURFACE APPLICATION: Applicable to modeling microbialite and carbonate reservoir diagenesis and lacustrine carbonate reservoirs.
STATUS: Project Proposed
TIMING: Proposed experiments
FUNDING: KICC seed funding.

Purpose

Our proposed research will focus on low-temperature dolomite formation in evaporative and lacustrine environments. The role of microbial surfaces in enhancing kinetics of low temperature dolomite (Kenward et al., 2013; Roberts et al., 2013) in a variety of environments and our recent work has suggested (Voegerl, 2014; Edwards et al., 2016) that microbial biomass may play a substantial role in dolomite formation in hypersaline and variable salinity environments. Mechanisms of dolomite formation are further clouded by the presence Mg-bearing clays (e.g. Bontognali et al, 2010), which can also nucleate via microbial biomass (e.g. Burne et al., 2014). Mg-bearing clay formation and subsequent dissolution in lacustrine microbialites underpin models for reservoir porosity formation and preservation (e.g. Tosca and Wright, 2015; Kenward et al., 2012) as well as dolomitization of calcium carbonate phases.

Our recent work in the alkaline lakes of the Sand Hills, Nebraska presents a natural analogue for lacustrine carbonate reservoir formation (e.g., Alonso-Zarza and Warme, 1990; Wright, 2012) as well as a rare location in which low temperature dolomite is currently forming. These lakes also host putative stevensite ((Ca0.5,Na)0.33(Mg,Fe^{++})3$Si_4O_{10}(OH)_2$•n(H2O)) formation in organic-rich, alkaline, saline fluids. Despite variation in salinity and concentrations of Mg and silica, yet persistently high pH and alkalinity in lakes, stevensite, calcite and aragonite are ubiquitous, while dolomite is only present in a single lake.

We will use experimental approaches that address the availability of Mg^{2+} in dolomite nucleation and precipitation in high pH, organic-rich, alkaline fluids. ***Our goal is to further investigate the role of organic matter in Mg^{2+}availability and dolomite nucleation, but investigating a range of fluid geochemistry that span lacustrine to sabkha. Results from this work will support a conceptual model for low temperature dolomite formation and produce quantitative data that can be incorporated into diagenetic models for dolomite reservoirs, including those that form in carbonate and mixed carbonate/siliclastic evaporative and lacustrine systems.***

Preliminary Results

We have devised an experimental protocol that produces disordered and ordered dolomite at 30°C in as few as five days. The protocol utilizes synthetic or dead organic matter with high carboxyl group densities that we hypothesize are responsible for the dehydration of Mg^{2+}, which is the rate-limiting step in dolomite nucleation at low-temperature (e.g. Roberts et al., 2013). These efforts provide a sound basis for experiments that will quantify rates and capture the heterogeneity of natural systems.

We now have the opportunity to apply these successful protocols to natural systems that are relevant to carbonate reservoir formation. Our preliminary results from alkaline, saline lacustrine environments in the Sand Hills of Nebraska, indicate extensive carbonate mineral formation, including dolomite, coincident with the clay mineral, stevensite (Figure 1). Because these lakes are saline (I=0.1-9M), they are also ideal locations to field test hypotheses about conditions that promote highly carboxylated organic matter, responsible for dolomite nucleation at low temperature (e.g. Roberts et al., 2013). Our results also show that microbial surfaces respond to increased salinity by increasing density of surface function groups, including carboxyl groups that dewater Mg^{2+} ions and promote dolomite formation. These results tie microbial physiology to environmental conditions and give insight into microbial controls on low-temperature dolomite precipitation in sabkha and lacustrine environments, yet the dataset still requires measurement of natural microbial consortia. We propose to utilize fluids and natural consortia from the Sand Hills lakes to further refine our organogenic model for low temperature dolomite formation and expand the model to include clay mineral phases, which may compete with carbonates for Mg^{2+}.

Proposed Project Description

The aim of the proposed research is use fluids and native microbial consortia from saline, alkaline lake systems to test our previous results that indicate carboxylated organic matter is responsible for the nucleation and precipitation of low temperature dolomite. While the results of the proposed work will refine this broad hypothesis, the use of geochemistry and microbial consortia from a modern alkaline lake system applies elucidated early diagenetic processes to lacustrine carbonate reservoirs.

The specific aims of this research are:

1. Measure the carboxyl group densities on native microbial consortia inhabiting a lacustrine environments in which fluids have high alkalinities and pH, with a range of salinities (0.1-9M).
2. Determine mechanistic controls on low temperature dolomite formation as a function of organic matter character, Mg/Ca ratios and silica concentration in fluids that represent alkaline, saline lakes and native and artificial organic matter.

These objectives will be accomplished using controlled laboratory experiments (e.g. Roberts et al., 2013) using native microbial consortia, carboxylated organic matter, native fluids as well as artificial fluids that mimic field conditions.

Deliverables

These experiments will validate previous success precipitating low temperature dolomite experimentally by extending the work to include conditions thought to form lacustrine carbonate reservoirs. These experiments underpin conceptual models for the formation of low-temperature dolomite via primary and replacement mechanisms and have implications for early diagentic reactions in other dolomite reservoirs as well.

Specific deliverables include: 1) Validation and refinement of quantitative model in which salinity primes microbial biomass for dolomite precipitation; 2.) Quantitative relationships between salinity, dolomite formation, and Mg-bearing clay formation that will further elucidate early diagenetic processes in lacustrine carbonate reservoirs; 3.) An MS thesis completed by Adam Yoerg; 4.) Presentations at the 2017/18 KICC Annual Meetings.

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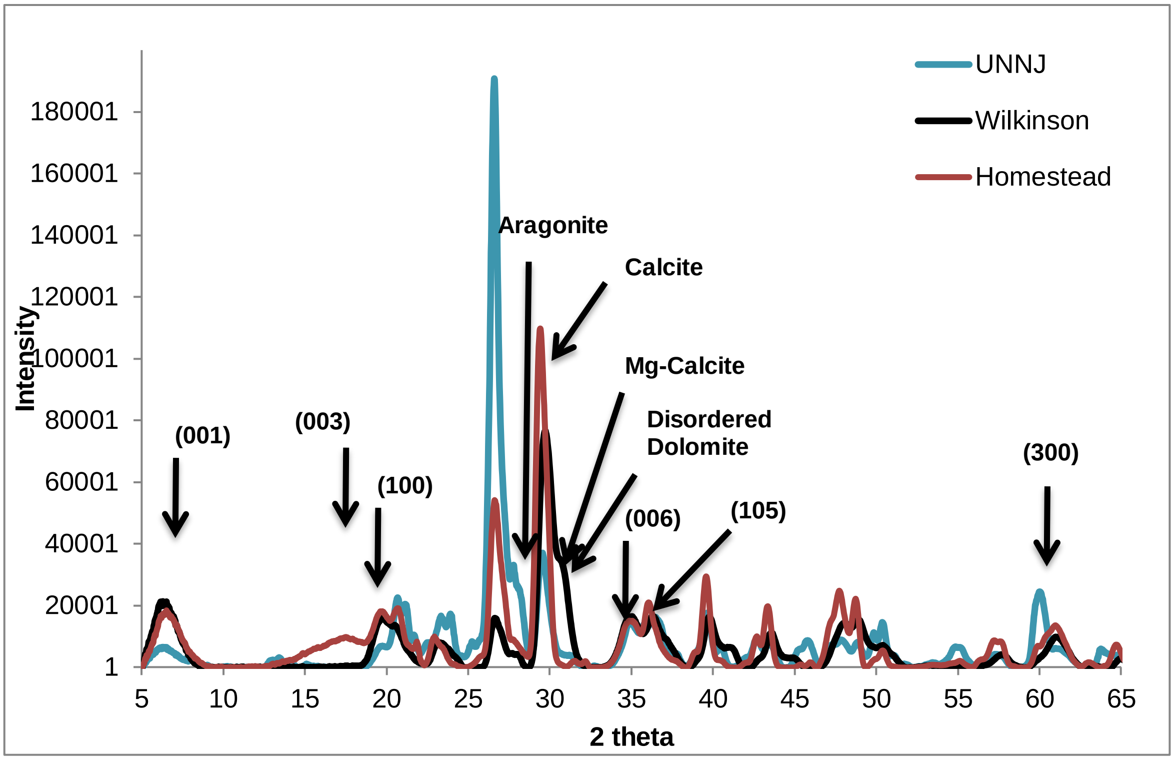

Figure 1. *XRD spectra of sediments from three alkaline, saline. All lakes contain calcite, aragonite, and putative stevensite. Dolomite and Mg-calcite only occur in one lake (Wilkinson).*

The Role of Carboxylated Organic Matter in Low-Temperature Dolomite Precipitation

Jennifer Roberts, David Fowle, Robert H. Goldstein and Craig Marshall

SUBSURFACE APPLICATION: Applicable to a variety of dolomite reservoirs; critical to modeling reservoir diagenesis.
STATUS: Project Proposed
TIMING: To be completed in the future if recommended by membership, funded, or staffed
FUNDING: KICC seed funding

Purpose

Recent work by our group has established that carboxylated organic carbon surfaces are necessary for achieving low-temperature dolomite precipitation (Roberts et al., in revision in dolomite-supersaturated solutions. Our success in synthesizing ordered, stoichiometric dolomite in less than 20 days at 30°C opens the possibility for easily performing controlled laboratory experiments that address the kinetics and thermodynamics of dolomite formation as well as stable isotope fractionation. Because the of the importance of dolomite as a reservoir rock, ***our goals are to use controlled laboratory experimentation to elucidate details of early dolomitization as a function of different types and abundances of carboxylated organic matter, and to evaluate how initial microbial phases seed systems for large scale precipitation***.

Project Description

Dolomite and limestone are effective hydrocarbon reservoirs, with 80% of North America's carbonate reserves accumulating in dolostones (Zenger et. al., 1980) due, in part, to their typically elevated porosity and permeability (Halley and Schmoker, 1983). Despite being abundant throughout the rock record, dolomite is uncommon in modern settings. Because dolostones are excellent reservoirs and abiotic synthesis of dolomite at low temperature has been difficult, research into the origin of massive dolomites is of interest to those in the petroleum industry. We hypothesize that:

- Organic matter with high densities of carboxyl group nucleate dolomite in dolomite supersaturated solutions by overcoming kinetic barriers;
- These dolomites may have distinct textural and morphological characteristics identifying this mode of formation in ancient rocks (Figure 1); and
- These early dolomite phases may serve as "seed" crystals for larger dolomite precipitation events in the presence of Mg-rich fluids.

These hypotheses will be tested using controlled laboratory batch experiments containing marine-type fluids with varying Mg:Ca ratios and a different types and quantities of organic matter. These reactors will be run until precipitation occurs at which time they will be: 1) characterized for rates of precipitation; 2) characterized for mineralogy using Raman spectroscopy, mineral chemistry and crystallinity, as a function of solution chemistry and the presence/absence of organic matter; and 3) analyzed petrographically to discern textural and morphological information to distinguish a "biological" signature.

Deliverables

We expect precipitation of low-temperature dolomite to be initiated by the presence organic matter with a high density of carboxyl groups. Due to the ability of carboxyl to dewater the Mg ion, these organic surfaces lower activation energy of nucleation, facilitating precipitation, forming highly crystalline phases that are more resist to recrystallization, thereby persisting through geologic time in order to serve as seed crystals for mass dolomite events.

Specific deliverables include: 1) Quantitative data to be implemented into kinetic models regarding the amount of biomass and specific geochemical parameters needed for precipitation; 2) petrographic information on distinctive "biological" signatures associated with carboxylated organic matter, 3) Information regarding isotope fractionation, particularly $\delta^{18}O$, and refinement of dolomite paleothermometers at low temperature, and 4) a conceptual model regarding this pathway of dolomite formation and subsequent seeding of dolomite precipitating system.

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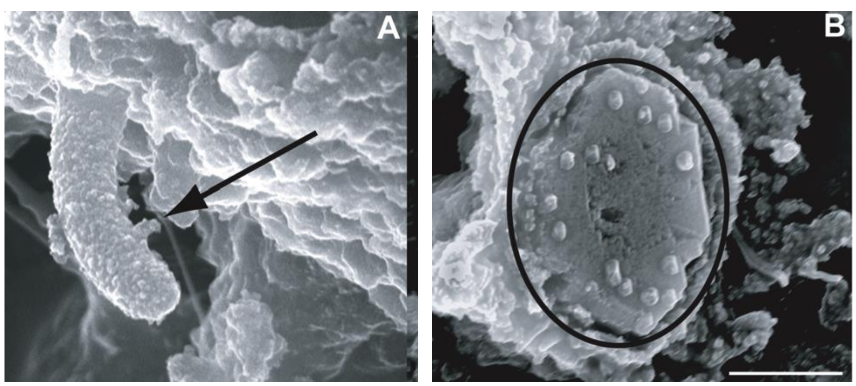

Figure 1. *Scanning electron photomicrographs of dolomite formed in freshwater in the presence of methanogenic microorganisms. A) A cell embedded in EPS and encrusted with dolomite. Arrow indicates one well-formed crystal. B) A more developed platy crystal of dolomite. Oval denotes boundary between EPS and crystal edge. Note nanoglobules in EPS. Images courtesy of Paul A. Kenward with special thanks to the University of Kansas MAI.*

Kinetics of Microbial Dolomite Precipitation and Incorporation of Kinetics into Porewater/Basin Evolution Models

Jennifer Roberts, David Fowle, and Robert H. Goldstein

SUBSURFACE APPLICATION: Applicable to a variety of dolomite reservoirs; critical to modeling reservoir diagenesis.
STATUS: Project Proposed
TIMING: To be completed in the future if recommended by membership, funded, or staffed
FUNDING: None

Purpose
This project will determine how ***microbes and associated organic matter control rates of carbonate dissolution, dolomitization, and cementation applicable to predictive models of porosity in carbonate reservoir and non-reservoir rocks.*** We will: 1) develop a quantitative model to describe the activity of Mg^{2+}, Ca^{2+}, HCO_3^-, and H^+ in association with the cell wall and other types of organic matter; 2) measure rates of carbonate precipitation as a function of cell wall and organic matter properties and fluid geochemistry; and 3) incorporate kinetic parameters into porewater/basin evolution models.

Project Description
The need for improved data on conceptual process and quantitative response is apparent in low-temperature meteoric systems. Even in very young meteoric systems, researchers continue to debate the relative importance of rate of fluid flow, CO_2 degassing near the water table, mixing at the water table, microbially controlled chemistry, and alteration of unstable minerals (e.g., Budd and Land, 1990). In this study, we investigate the role of microbial biomass and organic matter in enhancing rates of carbonate precipitation.

We hypothesize that:

- Charge density and functionality of organic matter and specifically microbial cells is the mechanism by which ions are dehydrated, often the rate limiting step for carbonate nucleation; and
- Microbial cell walls and some types of organic matter facilitate carbonate mineral precipitation and the kinetics of this reaction can be measured.

We will use controlled laboratory experimentation to test our hypotheses and quantify relationships between microbial cell walls and carbonate precipitation rates. We will: 1) characterize cell wall functional groups and charge density, defining reactivity with charged ions such as Mg^{2+}, using acid-base titration, and metal sorption experiments; 2) using these data, develop a surface complexation model (SCM) to describe the activity of Mg^{2+}, Ca^{2+}, HCO_3^-, and H^+ in association with the cell wall; 3) use flow-through experimental reactors to measure precipitation rates as a function of fluid geochemistry and biomass density; and 4) all kinetic parameters will then be integrated into porewater/basin evolution models (Figure 1), for example Geochemist's Workbench (Bethke, 2007) and reactive transport models such as TOUGHREACT (Xu et al., 2004).

Deliverables

We expect that microbial cell walls and some types of organic matter lower the activation energy of carbonate precipitation through the dehydration of ions on cell wall functional groups and that kinetic parameters that can be incorporated into geochemical and reactive transport models, allowing more precise modeling of early diagenetic relationships and prediction of the evolution of porosity in carbonate reservoirs.

- Define the bulk relationship between carbonate production and microbial biomass (or organic matter content) and functionality as a function of fluid geochemistry.
- Using these data, develop a surface complexation model (SCM) to describe the activity of Mg^{2+}, Ca^{2+}, HCO_3^-, and H^+ in association with organic surfaces.
- Quantify rates of carbonate formation and incorporate kinetic parameters into porewater/basin evolution models, providing a more robust treatment of microbial influences on precipitation kinetics.

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Salinity Controls on Microbial Cell Wall Character and Impacts on Microbially Mediated Precipitation of Carbonates

Jennifer Roberts and David Fowle

SUBSURFACE APPLICATION: Applicable to modeling carbonate reservoir diagenesis or testing hypotheses of "production-induced" diagenesis in produced carbonate reservoirs.
STATUS: Project Proposed
TIMING: Experiments already completed
FUNDING: KICC seed funding

Purpose

Recent microbial models and experimentation have demonstrated that dolomite precipitation is possible at low temperatures (<50°C) in laboratory settings, by microbial influence and mediation (e.g., Roberts et al., 2004; Mastandrea et al., 2006; Sánchez-Román et al., 2008). Many of these studies have observed dolomite precipitates that are intimately associated with microbial surfaces (Warthmann et al., 2000; van Lith et al., 2003) and recent studies have implicated microbial exopolymeric substances (Rivadeneyra et al., 1996; Dupraz et al., 2004; Sánchez-Román et al., 2007) in its formation (Krause et al. 2012). These recent studies demonstrate low temperature dolomite precipitation via nucleation on microbial surfaces that have high (>0.06 groups angstrom^{-2}) carboxyl-group densities (Roberts et al., 2013). Carboxyl-groups complex and dewater Mg^{2+}, favoring carbonation and subsequent nucleation and precipitation of dolomite. Our previous study demonstrated compelling evidence that carboxyl group density of microbial cell walls was determined by the salinity of growth solutions, with higher solution salinity correlated to higher carboxyl group density. These results suggest that environmental controls on salinity and *changing* salinity may be a primary control on microbial biomass surface character and therefore, microbially mediated carbonate mineral nucleation and precipitation.

Our goals in this proposal are to verify if solution salinity correlates to microbial carboxyl group density, the mechanism for low-temperature dolomite nucleation, utilizing additional organisms, focusing on seawater microorganisms and native consortia.

Project Description

Previous work with dolomite-forming and non-dolomite forming microorganisms demonstrate that carboxyl group densities increased by 275%, when doubling salinity concentrations for *Desulfovibrio brasiliensis*; increased by 170% when increasing salinity concentrations (16x) for *Shewanella putrefaciens*, and decreased by 47.5% when decreasing salinities by 75% for *Haloferax sulfurifontis.* The noted increases of carboxyl group density serve as evidence for environmental control on microbes.

The high-density values for *D. brasiliensis* and *H. sulfurifontis* are consistent with previous research that suggests that carboxyl group density (>0.6 sites Å^{-2}) is necessary for dolomite nucleation. These results, however, tie microbial physiology to environmental conditions and give insight into microbial controls on low-temperature dolomite precipitation in mixing zones, sabkha and hypersaline lagoon environments, yet the dataset is incomplete and does not encompass the wide range of seawater-type salinities found in marine environments.

The aim of the proposed research is to quantify the carboxyl group density of microbes that inhabit and are grown in salinity/ionic strength ranges similar to that of seawater to complete the data set that relates carboxyl group site density to ionic strength of growth medium shown in Figure 1, relate these data to our broader dataset and refine our conceptual model of where and when organic-matter-driven dolomite formation occurs. The specific aims of this research are:

3. Measure the carboxyl group densities on microbial cell surfaces for a collection of microbes that inhabit environments with seawater salinities.
4. Determine whether the concentration of carboxyl groups on microbial surfaces change as a function of growth medium ionic strength, and in cases where this occurs determine the rate at which density changes.

These objectives will be accomplished using controlled laboratory experiments with pure cultures grown at varying salinities and carboxyl group density will be quantified via quantification of proton adsorption to the site (e.g. surface titrations) (e.g. Fein et al., 2001). We have chosen a variety of organisms (Table 2) from a range of environments typical of carbonate formation, from freshwater lacustrine, to normal marine, and more evaporative marine settings.

Deliverables

If changes in salinity actively promote higher concentrations of carboxyl group density then we can define specific quantities of biomass necessary to nucleate carbonates and *predict* the timing and location of these nucleation events based on salinity distribution. These experiments underpin conceptual models for the formation of low-temperature dolomite via primary and replacement and therefore have implications for early diagentic reactions in dolomite reservoirs.

Specific deliverables include: 1) Validation and refinement of quantitative model in which salinity primes microbial biomass for dolomite precipitation; 2.) Quantitative relationships between salinity and carboxyl site density can be established and added to reactive transport models for early diagenesis; 3.) An MS thesis completed by Mathew Edwards.

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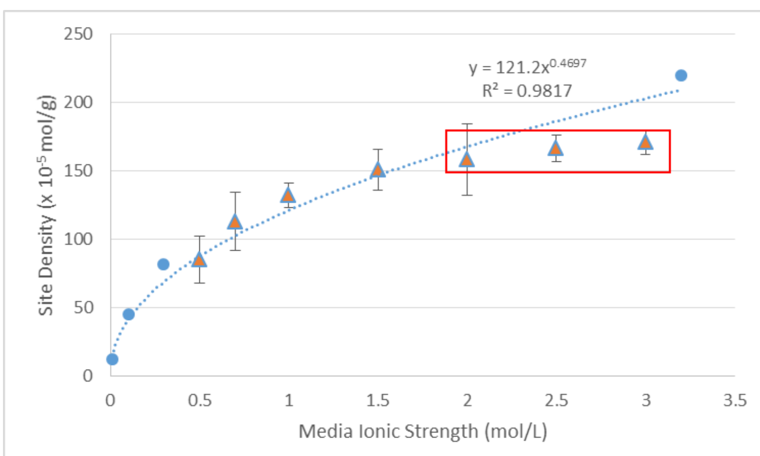

Figure 1. *Fitting a power function to the data shows the predictable relationship between functional group density and growth media ionic strength. Data in the red box are for 3 generations of growth of H. salinarum.*

Experimental Studies of Geofluid Interactions with Carbonate Rocks in Sedimentary Basins

Jennifer A. Roberts and David A. Fowle

SUBSURFACE APPLICATION: Applicable to modeling carbonate reservoir diagenesis or testing hypotheses of "production-induced" diagenesis in produced carbonate reservoirs.
STATUS: Project Proposed
TIMING: ongoing
FUNDING: KICC seed funding

Purpose

Due to experimental limitations, thermodynamic and kinetic data for mineral dissolution and precipitation typically are extrapolated to the temperatures and pressures appropriate for sedimentary basins. These data are central to reactive transport and basin evolution models used for prediction of reservoir quality. Extrapolation of these data are questionable, and new data from experiments conducted at conditions appropriate to the deep subsurface remain integral for understanding both the formation and evolution of porosity and permeability in sedimentary basins. Model experimental systems are critical to able to predict, for example, how fracking fluids or supercritical carbon dioxide will impact the integrity of shales and other seals, how mobile radionuclides, sourced from reservoir and seal dissolution, will behave in deep repositories, and how reservoir carbonates form and evolve under basinal temperatures and pressures (e.g. Cantucci et al., 2009; Kazuba et al., 2003). Furthermore, these systems lack any conceptual framework regarding the role of microorganisms in these processes, which are critical to the kinetics of many early diagenetic reactions below temperatures of 80 °C (e.g. clay diagenesis, carbonate cementation).

The goal of the proposed study is to generate preliminary data in our new high-temperature, high-pressure experimental geofluids laboratory generating rates of carbonate mineral precipitation and dissolution under reservoir temperatures and pressures.

Project Description

As principal investigators in a collaborative US Dept of Energy (DOE) project modeling carbon dioxide sequestration in a deep saline aquifer and a depleted oil reservoir, we have undertaken experiments to study shale cap rock dissolution, and precipitation reactions and kinetics at high temperatures and pressures in the presence of microbes and supercritical CO_2 at a DOE national lab. Specifically, we have developed protocols for high T and P experiments in batch reactors and flow through reactors that are comparable to reservoir conditions. The experimental data produced can be coupled to high-resolution x-ray CT scanning and *ex situ* geochemical and gas phase analysis to provide new mechanistic insights into diagenetic and reservoir reactions, products, and rates (after Regnault et al., 2009). Through funding in hand from the University for the experimental geofluids laboratory we propose to develop a line of research focused on Carbonate Reservoirs in collaboration with KICC and ultimately industry sponsors.

We will begin our studies by investigating the impact of a gradient of temperature and pressure on a variety of carbonate sediment samples, including primary dolomites produced in our laboratory (e.g. Kenward et al, 2013; Roberts et al. 2013), Arbuckle dolomite, and so-called "oil shales" (e.g. Pierson Formation) in the overlying Mississippian units. Specifically, we will 1.) investigate how mineral equilibria change under $CO_{2(SC)}$ injection, 2.) quantify the rates of dissolution and precipitation reactions, and 3.) assess how these reactions will impact reservoir and seal porosity and permeability. A critical and unique aspect of the proposed project will include microorganisms as a variable to investigate whether native microbial communities, their metabolic byproducts (e.g. organic acids, dissolved organic carbon) or cells themselves influence the rates, mechanism and outcomes of the previous questions. These experiments will be conducted using individual minerals, complex mineral mixtures and core samples from the basins of interest in collaboration with KICC and industrial partners. Fluid geochemistry and microbial communities will be modeled on reservoir brines characterized from drill stem tests and swab fluids. Reaction progress will be followed using solution chemistry, stable isotopes, pore and surface area measurements, XRD, and electron microscopy.

The initial work and deliverables for the proposed work will focus on reactions with Arbuckle and Mississippian materials in the presence of $CO_{2(SC)}$. We will also use this as an opportunity to observe "ripening" processes in our laboratory-precipitated dolomite, however these efforts will be purely exploratory at this point in time.

This work will provide a first step in understanding critical thermodynamic and kinetic parameters necessary to predict basin scale pore water and reservoir evolution based on sorption, precipitation/dissolution kinetics, and biological activity.

Deliverables

Specific deliverables include: 1) The first results for experimental microbial geochemistry of carbonates at high temperatures and pressures; 2.) Preliminary mechanistic, morphological and kinetic data on *in situ* of carbonate precipitation and dissolution with and without reactive microbial surfaces in the same environments, 3.) At least one manuscript and development of a larger NSF or industry supported proposal.

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Geophysical Signatures of Porosity, Fractures, and Facies in Conventional and Unconventional Rocks and Reservoirs

Outcrop and Holocene studies are invaluable for "ground truthed" data, but commonly are limited in the third dimension. Geophysics provides a means to indirectly explore variations in depositional and diagenetic character of carbonate systems in three dimensions. Employed in time-lapse mode, geophysical monitoring offers insights to the heterogeneous fluid-flow in carbonate systems. 3D reservoir models are placed into an exploration mode through synthetic seismic modeling and reservoir flow simulation. Examples of some current and pending projects include:

High-Resolution Shallow Seismic Imaging and Seismic Modeling of Upper Miocene Carbonates of the Agua Amarga Basin, SE Spain

George Tsoflias, Evan Franseen, Robert Goldstein, Hassan Eltom

SUBSURFACE APPLICATION: Tengiz and Korolev Fields in Kazakhstan, Miocene SE Asia, Avalon, Wolfcamp, Leonard, Bone Spring in Permian Basin, Cretaceous of Mexico
STATUS: Proposed project
TIMING: To be completed in the near future
FUNDING: None

Purpose

This project will employ shallow seismic reflection surveying and seismic modeling in order to provide high-resolution imaging and predict seismic response at reservoir conditions of deep-marine carbonate reservoir analogues of the Upper Miocene Agua Amarga Basin, SE Spain. Two-dimensional (2D) seismic profiles will be acquired, processed and integrated with existing three-dimensional (3D) geological models. Three-dimensional lithofacies and petrophysical models will be used to simulate synthetic seismic sections to assess imaging of internal reservoir architectures and the effect of carbonate facies variability on seismic signal response.

Project Description

Upper Miocene carbonates of the Agua Amarga basin in SE Spain are unique analogues for poorly studied deep-marine carbonate reservoirs (Franseen et al., 1998). A comprehensive geologic study of this area (Dvoretsky, 2009) resulted in detailed 3D models of lithofacies and petrophysical characteristics (porosity and permeability) (Figure 1). Two types of reservoirs were distinguished based on mechanism of deposition: 1) dispersed-flow deposits forming thin and highly heterogeneous accumulations and 2) focused-flow deposits resulting in relatively thick and uniform deposits. The first type is widely recognized and it is considered a poor reservoir, while the second one is an attractive target for exploration but it is poorly studied and might be more common than previously thought. Shallow seismic methods can provide high-resolution imaging of the subsurface at the reservoir scale (sub-meter to tens of meters) and can yield information about stratigraphy, facies distribution and fracture properties.

Expanding on the work of Dvoretsky (2009), high-resolution 2D seismic data will be acquired over dispersed-flow and focused-flow deep-marine carbonate reservoir analogues. Three-component (3C) data will be acquired in order to obtain both compressional and shear wave velocities. P- and S-wave velocities are critical in exploration geophysics for predicting lithologies and for estimating the petrophysical properties of carbonate rocks (e.g. Verwer et al., 2008; Anselmetti et al., 1997). Although near-surface conditions are drastically different than deeply buried reservoirs, it is expected that reservoir analogue seismic studies will offer insights about relative changes of seismic properties across varying carbonate lithofacies. Seismic signal attributes, such as the dependence of reflectivity to angle of incidence (AVO) will be tested in the field to assess their utility in hydrocarbon exploration of deep-marine carbonate reservoirs.

Seismic modeling will employ velocities estimated in two different ways: 1) from literature datasets of similar facies and age (e.g. Verwer et. al., 2008); and 2) from dual porosity models (e.g. Baechle et al., 2008; Weger et al., 2009). Baechle et al. (2008) showed that seismic velocities of carbonate rocks are mostly affected by the amount of micropores (pores less than 30 microns), while macroporosity controls permeability (Figure 2). Known total porosity and permeability values at the Agua Amarga Basin (from Dvoretsky, 2009) will be used to estimate micro- and macroporosities, and subsequently, seismic velocities will be calculated as a function of microporosity.

In many carbonate reservoirs fractures control permeability and therefore their orientation and density is of great importance for oil and gas exploration. Radial, 3C seismic survey will be conducted to assess azimuthal velocity anisotropy of the carbonate reservoir analogues as in Lu et al. (2009).

Deliverables

Seismic imaging of the deep-marine carbonate reservoir analogues along with modeling of petrophysical properties will assess characteristic elastic properties (e.g. P- and S-wave velocity, AVO) of focused-flow deposits and dispersed-flow deposits on seismic data that could offer insights to the response of exploration scale seismic data. In addition, high-resolution seismic imaging or the reservoir analogues will improve our understanding of the distribution of carbonate lithofacies and fractures.

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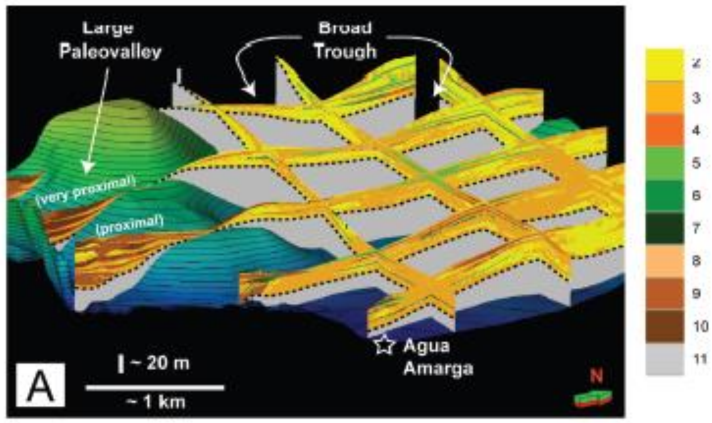

Lithofacies	Lithofacies Integer
Foraminiferal ws/ps	2
Volcaniclastic foraminiferal ws/ps	3
Skeletal foraminiferal ws/ps	4
Graded fn-med skeletal ps	5
Graded crs skeletal ps	6
Graded v.crs skeletal ps	7
Breccia: fn matrix	8
Breccia: med matrix	9
Breccia: crs-v.crs matrix	10
Volcaniclastic skeletal ps/gs	11
Skeletal gs	11

***Figure 1**. Lithofacies fence diagram: large paleovalley is associated with focused-flow deposits; broad trough is associated with dispersed-flow deposits (from Dvoretsky, 2009).*

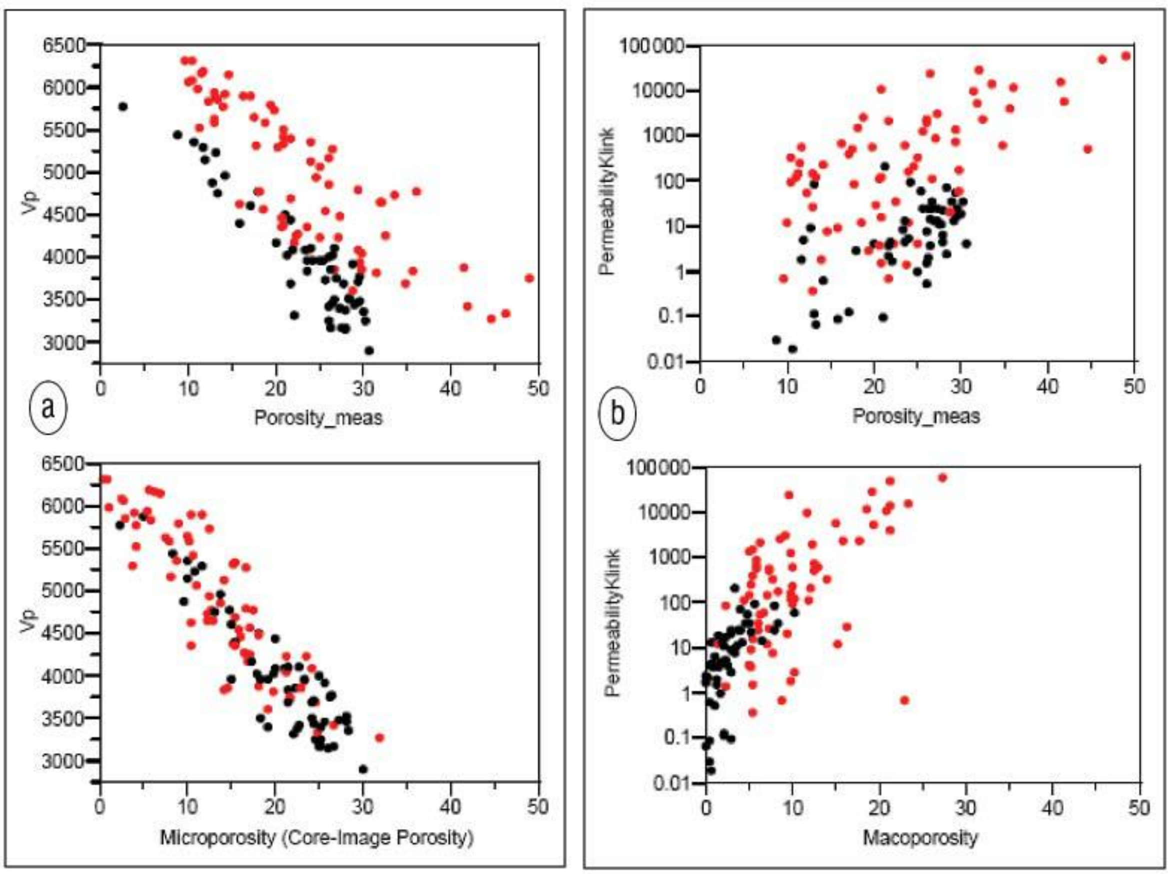

***Figure 2.** a) Top: porosity versus p-wave velocity. Bottom = microporosity versus p-wave velocity. Black dots (samples with microporosity) have smaller scatter in the plots than red dots (samples with less microporosity). The porosity-velocity relationship is considerably improved by using microporosity instead of total porosity; b) Top: porosity versus permeability. Bottom: using macroporosity instead of total porosity improves a porosity-permeability correlation. (from Baechle et al., 2008).*

Ground Penetrating Radar High-Resolution 3-D Imaging of Dual Porosity - Permeability Systems: Imaging Carbonate Lithofacies, Flow Units and Flow Conduits

George Tsoflias, Student

SUBSURFACE APPLICATION: Advancing GPR imaging methods will support the 3D study and quantification of carbonate reservoir analogue properties.
STATUS: Long-term project in progress
TIMING: Significant results to be reported – Results currently available to membership
FUNDING: Partial from US DOE

Purpose

High-resolution geophysical imaging of the subsurface offers a means to assess heterogeneous properties of carbonate reservoir analogues in 3-D. This project aims at advancing ground penetrating radar methods for imaging internal architectures of carbonate systems, characterizing lithofacies, quantifying porosity distribution, and identifying flow units and flow conduits. Technological developments under this project are applied to KICC outcrop studies advancing the understanding of hydrocarbon reservoir properties.

Project Description

Ground penetrating radar is a high-resolution imaging method that has been used in numerous studies of carbonate outcrops (e.g. Franseen et al., 2007). GPR uses FM frequency radio waves to image the subsurface at decimeter-scale resolution (Davis and Annan, 1989). Radar waves respond to changes in formation porosity as well as pore-fluid type. Used in 3-D and time-lapse mode, GPR imaging can provide high-resolution images of internal architectures and monitor the flow of fluids (Tsoflias et al., 2001; Grasmueck and Weger, 2002). This project focuses on the development of quantitative GPR methods for the study of dual porosity – permeability rocks. Dual porosity rocks are highly heterogeneous and present a great challenge to fluid flow properties prediction. In those units, fracture and dissolution networks provide the flow conduits for rapid transport of fluids. A priori knowledge of fracture and dissolution conduit orientation, inter-connectivity and aperture variability, as well as matrix porosity and permeability heterogeneity, can significantly improve our understanding of carbonate system flow properties. Relating quantitative GPR signal response to formation porosity distribution and hydraulic properties can assist in the study of ground water aquifers and near-surface petroleum reservoir analogues.

Our earlier work has exploited GPR methods to study carbonate rocks. Three-dimensional GPR reflection surveying has imaged varying carbonate lithofacies, lithologic discontinuities, dissolution zones, and horizontal fractures (Figure 1). Velocity analysis of common mid-point data identified velocity variations correlating to alternating open and restricted marine facies (Figure 2). Analysis of GPR reflection amplitude variation along prominent flow conduits revealed centimeter-scale fracture aperture variation and mapped flow conduits and flow barriers in three dimensions. Employed along with hydrologic and stratigraphic information, 3-D GPR methods are shown to remotely characterize the flow properties of heterogeneous carbonate systems (Tsoflias, 2008).

Deliverables

The proposed work will develop quantitative methods of relating GPR signal attributes to carbonate system heterogeneous flow properties by investigating the relationships of electromagnetic (EM) signal response (i.e. amplitude, phase, velocity, frequency) to hydraulically important formation parameters (i.e. conduit aperture, matrix porosity, fluid type and electrical conductivity) (e.g. Tsoflias et al, 2004; Tsoflias and Becker 2008). The methods will be used in conjunction with KICC geologic outcrop studies for the development of 3-D carbonate flow system analogues. GPR determination of facies and porosity distribution, conduit aperture, interconnectivity, channeling, and conduit density will be integrated with reservoir simulation studies for prediction of carbonate reservoir performance.

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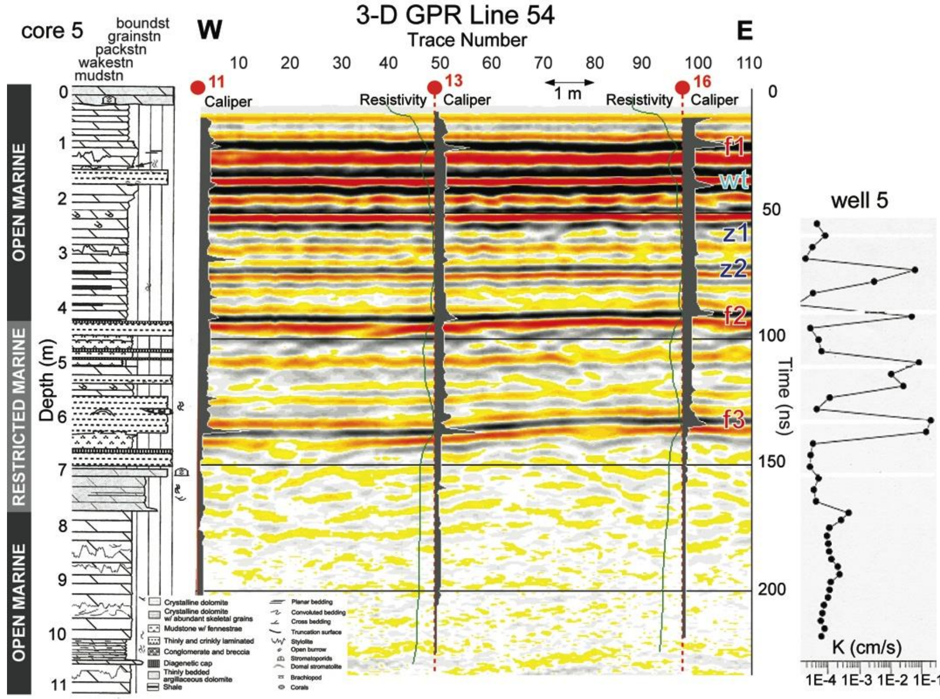

Figure 1. *200 MHz GPR data along with a stratigraphic log and hydraulic conductivity profile (borehole data provided by WGNHS; hydraulic conductivity from Muldoon and Bradbury, 1998; stratigraphic log from Simo et al., 1998). Reflections correlate spatially to horizontal flow conduits such as fractures (f1, f2 and f3), a dissolution zone (z1) and a diagenetic zone (z2). The top of the saturated zone (wt) is at 2 m.*

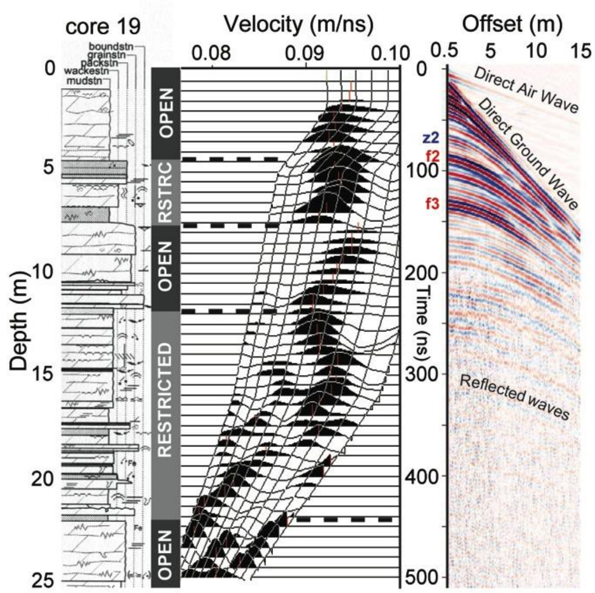

Figure 2. *Stratigraphic log, GPR velocity spectrum and corresponding CMP. GPR stacking velocity segments correlate to distinct open and restricted marine lithofacies and are separated by sharp velocity breaks identified by horizontal dashed lines. (right top) Fracture GPR reflection amplitude maps corresponding to f2 and f3 identified in figure 1.*

Imaging Fluid Flow and Transport in Discrete Fractures Using Ground Penetrating Radar

George Tsoflias, Student

SUBSURFACE APPLICATION: Advancing the fundamental understanding of flow through fractured rocks.
STATUS: Long-term project in progress
TIMING: Significant results to be reported – Results currently available to membership
FUNDING: Partial from US DOE

Purpose

Accurate prediction of fracture flow properties is critical to the efficient development of reservoirs. Flow in fractured formations is highly heterogeneous and difficult to predict. The objective of this work is to study fractured near-surface reservoir analogues for remote determination of fracture hydraulic properties and time-lapse monitoring of flow of fluids using GPR. Recently developed GPR methods of monitoring ground water flow will be extended to imaging multi-phase flow through fractures and monitoring the efficiency of enhanced oil recovery methods. High-resolution field imaged fracture properties will be incorporated to reservoir flow model simulations.

Project Description

Predicting flow and transport in fractured formations remains a challenging problem. Flow through this highly heterogeneous medium is controlled by fracture aperture, channeling along the fracture (i.e., aperture variability), and fracture connectivity. Our earlier work has developed GPR methods for imaging fractures and mapping aperture variability (Figure 1) (Tsoflias, 2008), differentiating between air filled (drained) and water filled (saturated) portion of a fracture plane during hydraulic testing (Figure 2) (Tsoflias et al., 2001), and identifying variations in fracture water salinity (Figure 3) (Tsoflias and Becker, 2008).

This research is developing GPR methods to obtain an independent measure of the spatial distribution of fracture aperture and fluid tracer concentration. We are investigating the GPR response of water saturated fractures of varying aperture containing native formation water or a saline tracer of varying concentration. For a fracture enclosed in a homogenous matrix, reflection amplitude is expected to increase from a value of zero for zero layer thickness to maximum reflection strength when layer thickness is approximately equal (depending on wavelet shape) to ¼ of signal wavelength (λ) in the medium filling the fracture. EM theory also predicts that electrically conductive (lossy) media yield complex reflection and transmission coefficients that result in signal phase shift (Straton, 1941). The Fresnel equations describe the dependence of the complex reflection coefficient to layer thickness, electrical conductivity, permittivity, signal frequency, angle of incidence and wavefield polarization. Our work including field experiments, analytical solutions of the Fresnel equations and FDTD numerical simulations has shown that at a fractured geologic setting a saline tracer will cause a characteristic and predictable change to the reflected GPR signal amplitude and phase. This new understanding of GPR response to fracture properties allows us to remotely measure fracture aperture, predict fluid content and measure tracer concentration.

The ongoing investigation is developing GPR methods for remote, quantitative characterization of fracture flow and transport properties (e.g. Becker and Tsoflias, 2010; Tsoflias et al., 2015). The proposed work will further advance the GPR theoretical, modeling and reservoir analogue field work to study fracture flow of multiple phase fluids analogous to hydrocarbon reservoirs. Field investigations will monitor flow through discrete fractures of water, water-air, vegetable emulsions of varying viscosity to simulate oil, and fluids of varying salinity to quantify fracture transport properties and monitor flow through formation matrix. Field GPR experiments will also monitor the efficiency of reservoir analogue simulated enhanced oil recovery methods, such as gelled polymers developed by KICC's TORP to control flow through fractures in oil reservoirs. Furthermore, the GPR methods will be applicable to radar observations that could be made in boreholes, allowing fracture imaging of a region extending 10 to 30 m away from the borehole and down to borehole depths of actual hydrocarbon reservoirs. Such methods could prove useful to the development of new electromagnetic based downhole technologies for hydrocarbon exploration.

Deliverables

The proposed work will advance GPR methods for remote, quantitative characterization of flow and transport properties of fractured hydrocarbon reservoir analogues. The new GPR methods will allow the study of flow in well understood near surface reservoir analogues by simulating multiphase flow and fluid types found in hydrocarbon reservoirs. Quantitative observations of flow and transport through fractures and matrix will be integrated with reservoir simulation studies for prediction of hydrocarbon reservoir performance.

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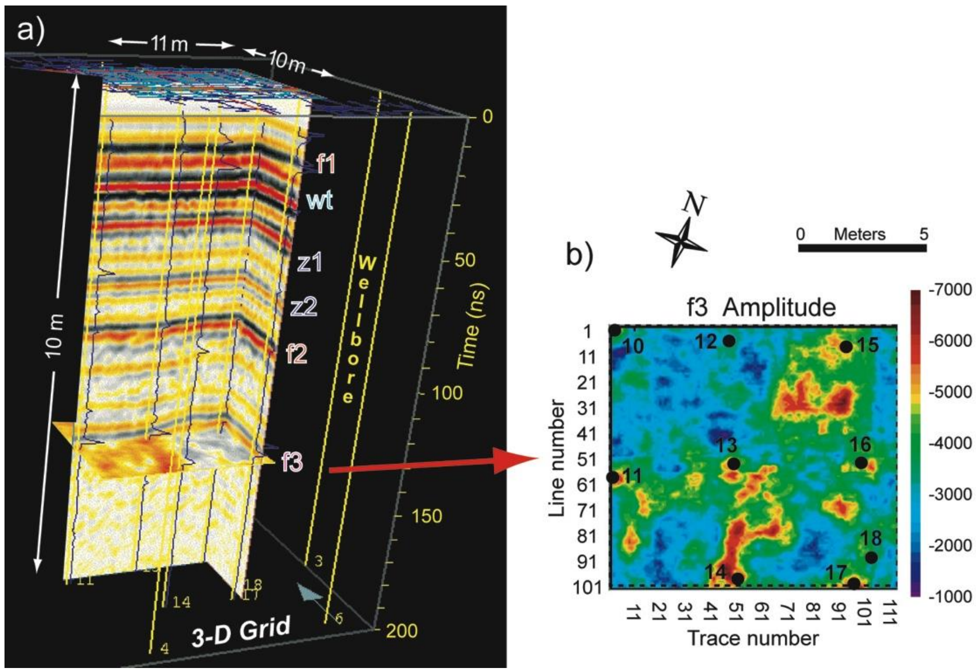

***Figure 1**. a) Perspective view of a 200 MHz 3-D GPR data displayed along with wellbores and caliper log curves (blue curves). Distinct reflections correlate spatially to horizontal fractures (f1, f2 and f3). b) GPR reflection amplitude map of f3. Well locations are shown as solid circles (after Tsoflias, 2008).*

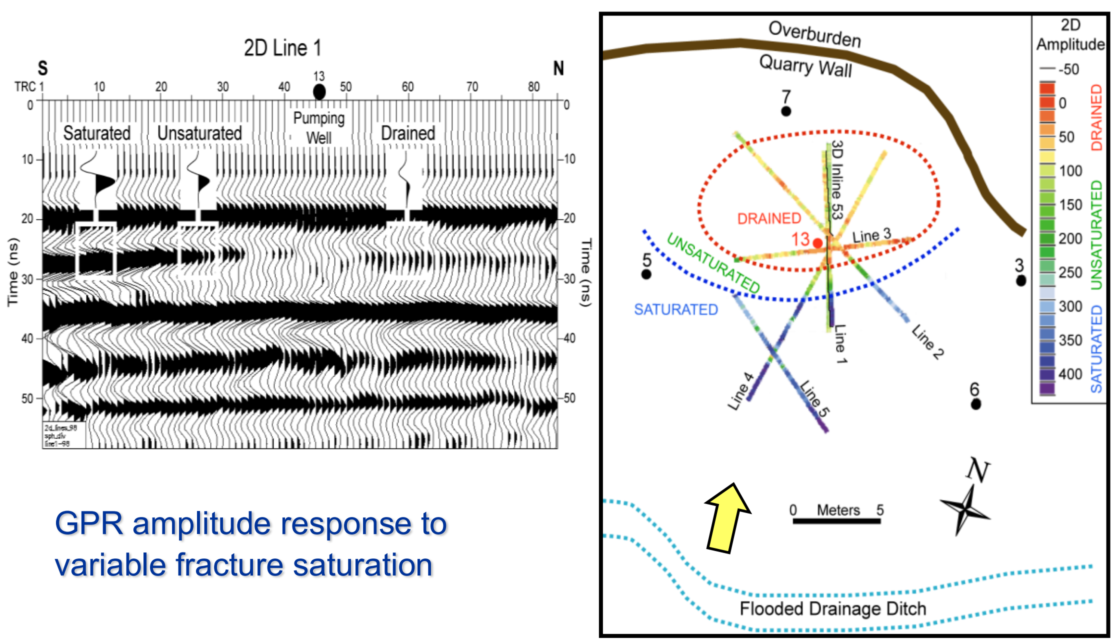

***Figure 2**. (left) GPR line during pumping test at well 13. Single trace inserts of the FDTD modeled waveforms for saturated, partially saturated and drained fracture models, are shown along with the corresponding recorded waveforms outlined by white boxes. (right). Amplitude map of the 28 ns peak during pumping at well 13.*

Seismic Characterization of Carbonate Reservoirs in Kearney Co., West KS: Patterson & Hartland Fields

George Tsoflias and students

SUBSURFACE APPLICATION: Seismic characterization of western KS carbonate reservoirs Osage, Viola, and Arbuckle. Evaluation of post- and pre-stack seismic analysis methods for prediction of reservoir heterogeneous properties and the assessment CO_2 storage potential in Western KS.
STATUS: Long-term project in progress
TIMING: To be completed in the future, funded and staffed
FUNDING: Partial from United States Department of Energy

Purpose

Carbonate reservoirs are heterogeneous and the distribution of properties controlling the flow of fluids is difficult to predict. Seismic characterization of carbonate reservoirs is challenging and the subject of extensive research. Work completed by Tsoflias and students at Wellington field in south-central Kansas identified characteristic relationships between Mississippian and Arbuckle reservoir properties (thickness, porosity) and seismic attributes (Amplitude Variation with Offset – AVO, P- and S-Impedance), and developed seismic inverse workflows that predicted accurately porosity distribution (Tsoflias et al., 2017; Tsoflias et al., 2015). In addition, analysis of azimuthal anisotropy (AVAZ – Amplitude Variation with Azimuth) successfully mapped fracture density and orientation in the Mississippian and Arbuckle reservoirs. Monitoring of a CO_2 injection in the Mississippian validated reservoir properties predicted by seismic AVAZ (Tsoflias et al., 2019).

The objective of this project is to employ 3D seismic imaging for quantitative characterization of Osage, Viola and Arbuckle reservoir properties in western Kansas in order to assess their potential for CO_2 storage. This work will add new seismic case studies of carbonate reservoir characterization to KICC research and it will expand our areas of study in the US midcontinent.

Project Description

As part of US DoE funded research, this project aims to evaluate carbonate reservoirs in Kearney Co., West Kansas for CO_2 storage potential. Two new 3D seismic surveys will be acquired at Patterson and Harland fields and merged with the existing Heinitz field 3D (Figure 1). The Osage, Viola and Arbuckle carbonate reservoirs will be targeted (Figure 2). Two new wells will be drilled and cored. Reservoir tests will inform reservoir models. Three dimensional seismic will be integrated with well, core and engineering data. This work will offer insights on seismic imaging and seismic characterization of the Osage, Viola, and Arbuckle groups by employing the methodologies developed previously at Wellington field (AVO and AVAZ). Well and core data will be used to calibrate pre-stack seismic models for prediction of porosity distribution and discrete fracture networks in the three carbonate reservoirs of interest. In addition, shale units in the Meramec, Morrow, Cherokee, and Atoka that overly the carbonate reservoirs will be evaluated for their effectiveness as regional seals.

Technology developed through this project will be beneficial to KICC sponsors exploring the midcontinent and can offer insights to carbonate reservoir characterization in other regions where KICC sponsors explore.

Deliverables

i) Comprehensive assessment of *post- and pre-stack* seismic attribute analysis of Patterson and Hartland 3D seismic surveys
ii) Evaluation of AVO and AVAZ analysis methods for prediction of porosity and fracture density distribution at Osage, Viola, and Arbuckle carbonate reservoirs
iii) Acoustic and elastic impedance inversion volumes and predicted reservoir porosity and fracture network maps
iv) *Post-* and *pre-stack* seismic analysis workflows for Osage, Viola, and Arbuckle carbonate reservoirs

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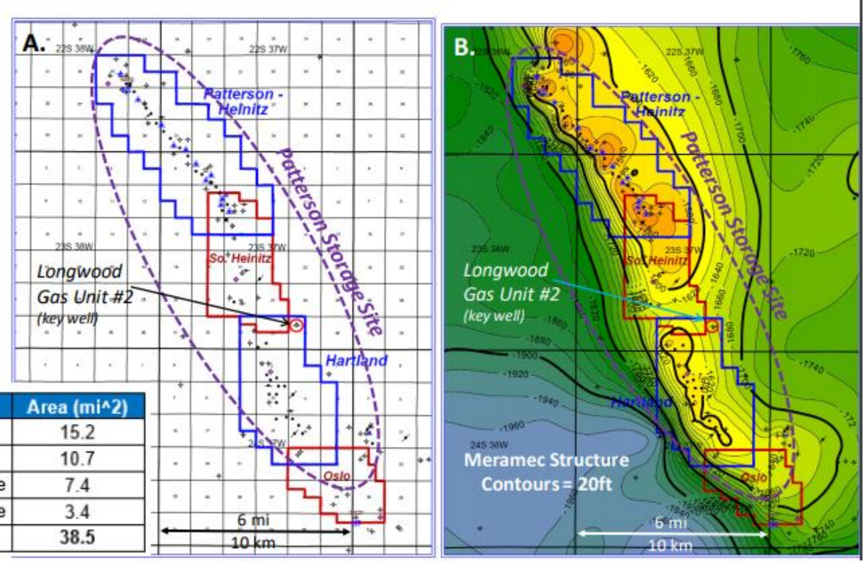

Name of Shoot	Status	Area (mi^2)
Patterson	proposed	15.2
Hartland	proposed	10.7
Heinitz South	acquire license	7.4
Oslo	acquire license	3.4
Total		**38.5**

Figure 1. *Acquisition of 3D seismic over the Patterson, Heinitz, and Hartland fields (Dubois 2019, pers. comm).*

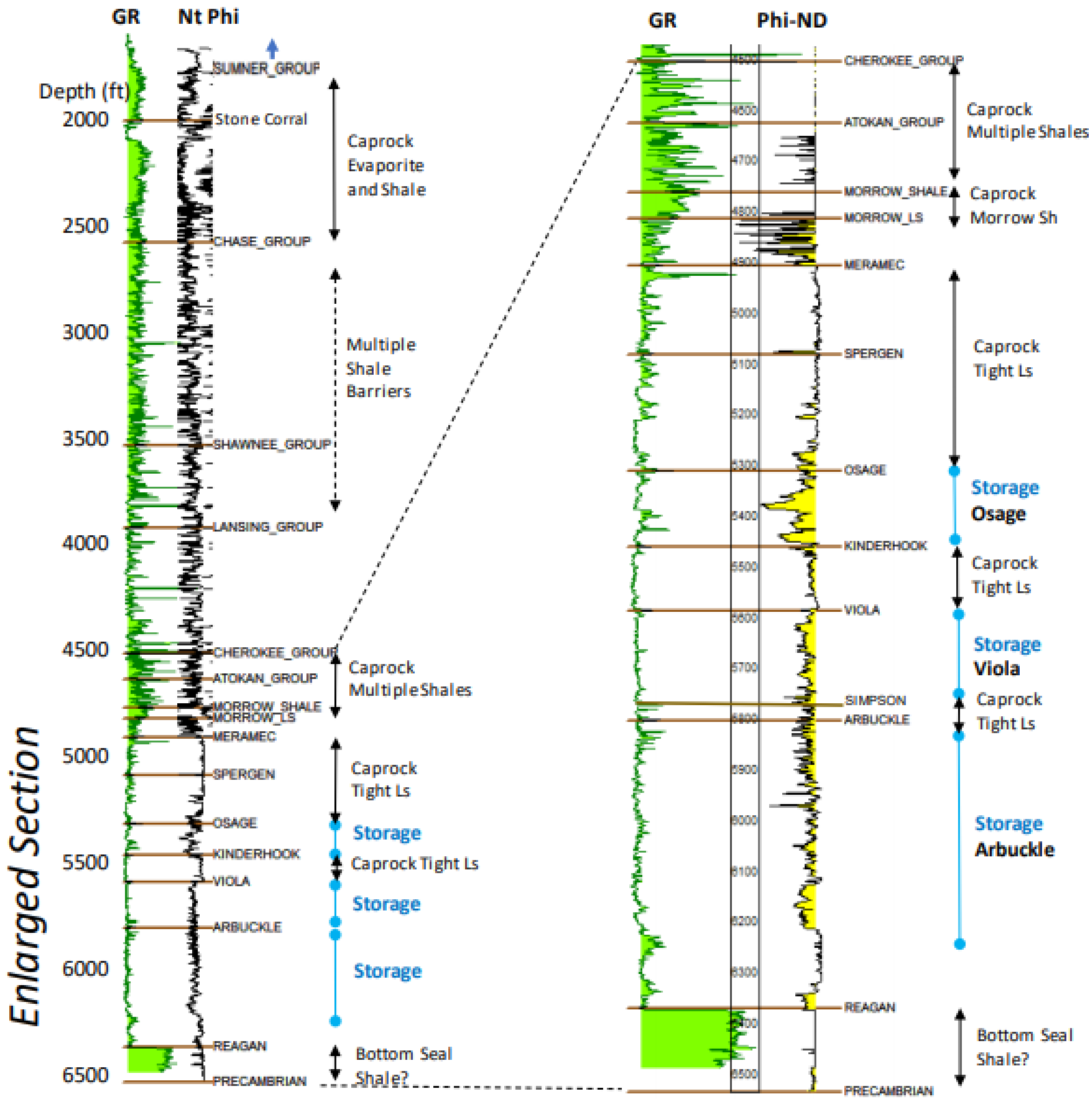

Figure 2. *Stratigraphic Column with reservoir (storage) and seal (caprock) units identified (Dubois, 2019, pers. comm).*

Post-Stack Seismic Attribute Analysis and Impedance Inversion for Characterization of the Mississippian Reservoir, South-Central Kansas

George Tsoflias, Lynn Watney, Ayrat Sirazhiev

SUBSURFACE APPLICATION: Seismic characterization of Mississippian carbonate reservoirs. Assessment of post-stack seismic analysis methods for prediction of carbonate reservoir heterogeneous properties.
STATUS: Project completed and not yet published
TIMING: Significant results to be reported – Results currently available to membership
FUNDING: Partial from United States Department of Energy

Purpose

Mississippian chert reservoirs are important hydrocarbon resources in North America. These reservoirs are highly heterogeneous, typically below seismic resolution and, therefore, challenging to characterize using seismic data (e.g. Mazzullo et al., 2009; Montgomery et al., 1998; Rogers and Longman, 2001; Watney et al., 2001). In this study we conducted a seismic attribute analysis of the Mississippian chert reservoir at the Wellington Field, south-central Kansas using well-log and 3D (PSTM) seismic data. The microporous cherty dolomite reservoir exhibits a characteristic vertical gradational porosity reduction and associated increase in acoustic velocity, known as a ramp-transition velocity function. The primary objective of this study was to investigate possible relationships of the reservoir thickness and porosity with post-stack seismic attributes, including inverted acoustic impedance.

Project Description

We examined the seismic response of a ramp-transition velocity function in order to predict the thickness of the Mississippian chert reservoir. The Mississippian top is characterized by a vertical gradational porosity decrease and a corresponding ramp velocity increase that results in a gradational impedance increase (Figure 1). We employed seismic wedge modeling using both synthetic and original sonic logs to aid the interpretation and investigate the resolution limits of the seismic data. A characteristic amplitude decrease, wavelength increase (frequency decrease) and 90-degree phase change are observed at the top of the Mississippian as reservoir thickness increases. Seismic amplitude is shown to predict reliably reservoir thickness in the range of 5-25 m when a well-defined porosity reduction is present (Figure 2).

Post-stack model-based inversion of the seismic data was used to derive the acoustic impedance model of the subsurface. The resolution of the model-based inversion was evaluated for the case of the gradational impedance increase within the Mississippian reservoir interval using synthetic wedge models. Multilinear regression analysis is used to transform the inverted acoustic impedance to porosity distribution within the Mississippian reservoir (Figure 2). The reliability of the predicted porosity model is tested by cross-validation during the multilinear regression analysis.

Results of this research could benefit the characterization of similar chert as well as clastic and carbonate reservoirs characterized by downward porosity reduction. In addition to predicting the reservoir porosity and thickness, the seismic response of a ramp-transitional velocity function related to downward porosity reduction might be useful in understanding depositional and diagenetic histories of such reservoirs.

Key Findings

- A gradational porosity decrease at the top of the Mississippian reservoir corresponds to a gradational P-wave velocity increase
- A gradational or "ramp" velocity function results in the integral of the seismic wavelet with lower amplitude, lower frequency content and waveform phase change
- The characteristic seismic amplitude response of the top of the Mississippian is used to predict reservoir thickness when true thickness is 1/16λ-5/16λ (5–25 m)
- Post-stack model-based acoustic impedance inversion provides reliable porosity predictions for reservoir thickness range of 1/8λ-7/16λ (10-35 m)

Deliverables

v) Seismic attribute analysis methods of gradational (ramp) velocity profiles such as the Mississippian Chert at Wellington Field.

vi) Calibration of seismic amplitude and acoustic impedance inversion to reservoir thickness and porosity distribution respectively.

vii) Mississippian reservoir thickness map over the extent of the 3D seismic data.

viii) Acoustic impedance volume and derived Mississippian reservoir porosity distribution at Wellington field.

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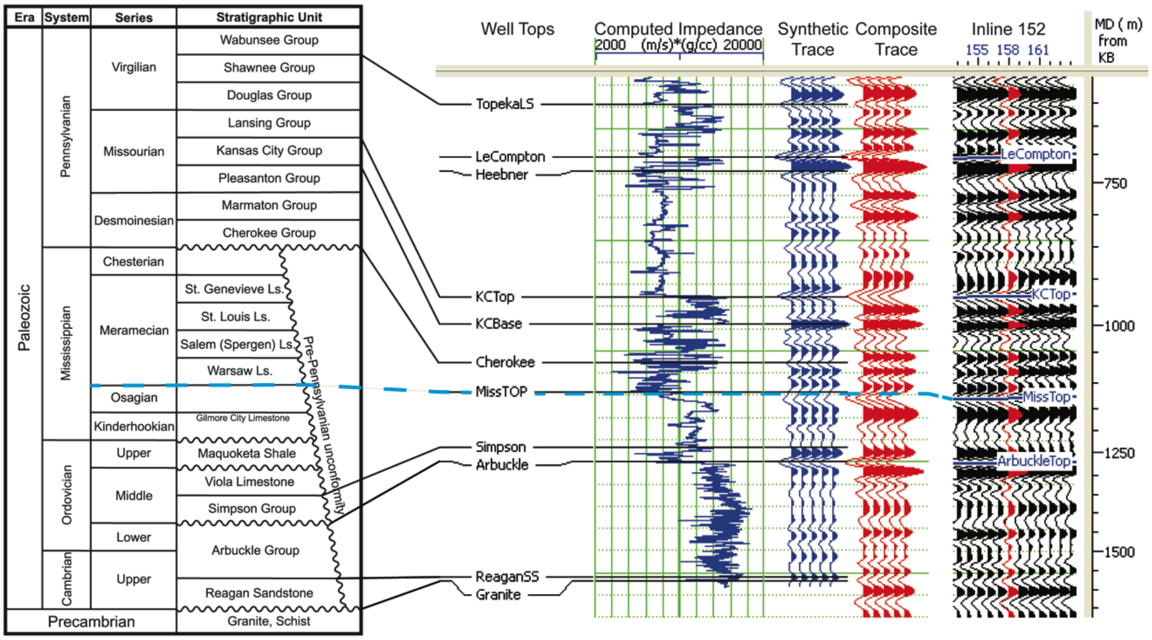

***Figure 1**. Generalized stratigraphic section of central Kansas (from Nissen et al. (2009), originally from Cansler (2000));impedance log and synthetic seismogram at well #15-191-22591.*

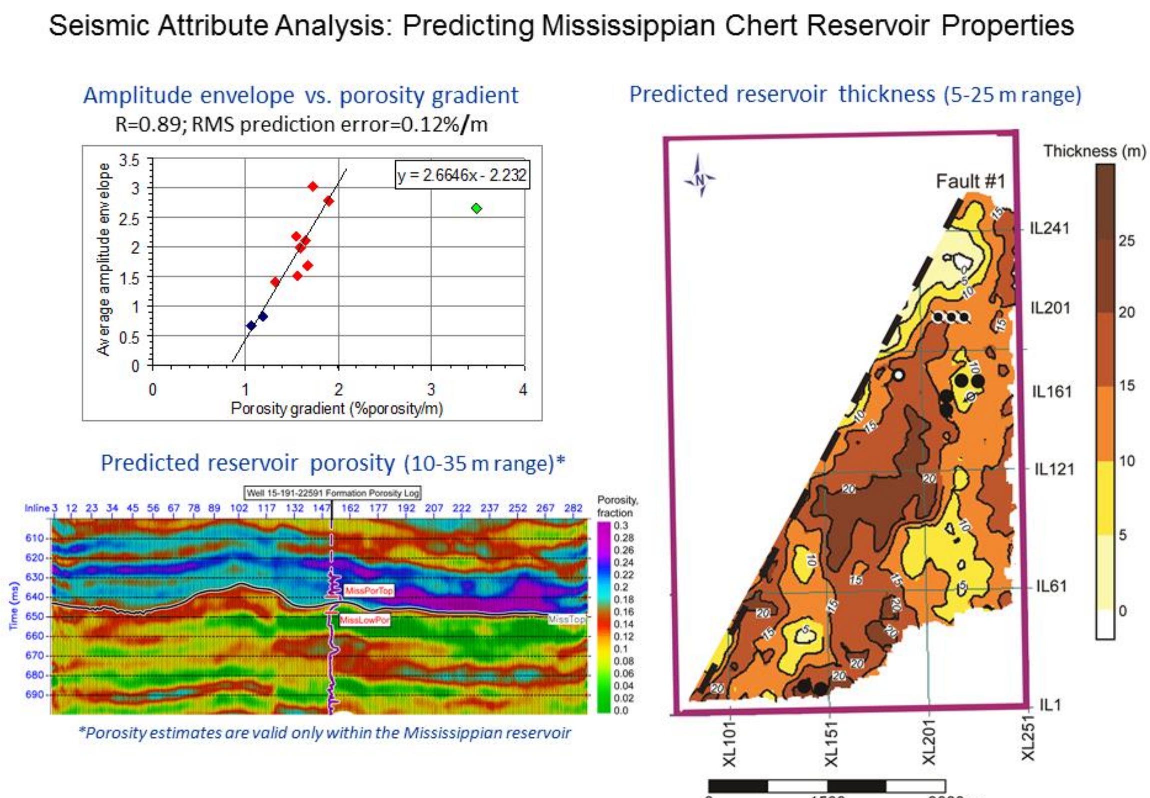

***Figure 2.** (top left) Relationship of porosity gradient to seismic amplitude. (right) Reservoir thickness inferred from seismic amplitude. (lower left) Porosity prediction from inverted acoustic impedance with overlain original formation porosity log at well #15-191-22591.*

Porosity Prediction and Flow Unit Identification in the Mississippian and Arbuckle Reservoirs Using Seismic AVO Analysis and Pre-Stack Seismic Simultaneous Inversion

George Tsoflias, Lynn Watney, Yousuf Fadolalkarem

SUBSURFACE APPLICATION: Determination of Mississippian and Arbuckle carbonate reservoir porosity and distribution of flow units. Assessment of pre-stack seismic analysis methods (AVO, simultaneous inversion, multiattribute regression) for prediction of carbonate reservoir heterogeneous properties.
STATUS: Project completed and not yet published
TIMING: Significant results to be reported – Results currently available to membership
FUNDING: Partial from United States Department of Energy

Purpose

The Mississippian and Arbuckle reservoirs in the US mid-continent have been major hydrocarbon producers and are targets for enhanced oil recovery operations as well as CO_2 sequestration projects (Franseen et al., 2004; Mazzullo et al., 2009; Rogers and Longman, 2001; Watney et al., 2001). Furthermore, resurgent industry interest in the Mississippi Lime play is resulting in increased interest in carbonate reservoirs. Seismic imaging is the primary industry method for exploration and development of hydrocarbon resources. However, carbonate reservoirs are heterogeneous and the distribution of properties controlling the flow of fluids is often below seismic resolution. Identifying characteristic relationships between reservoir properties (i.e. thickness, porosity, density, fracture sets, flow baffles/conduits) and seismic response (amplitude, frequency, phase, offset, azimuth) is critical to assessing hydrocarbon resources.

The objectives of this research are to: a) Assess the capability of pre-stack seismic analysis methods (Amplitude Variation with Offset –AVO; simultaneous inversion of AVO data for P- & S-impedance and density) to quantitatively predict Mississippian and Arbuckle Reservoir properties in South-Central Kansas, and b) Develop seismic data interpretation workflows applicable to the region for carbonate reservoir characterization.

Project Description

This project expanded previous work of predicting Mississippian Chert reservoir thickness and porosity distribution using 3D P-wave *post-stack* seismic amplitude and acoustic impedance at the Wellington field in South-Central Kansas. This research focused on the Mississippian and Arbuckle reservoirs. It investigated 3D P-wave *pre-stack* seismic data analysis, Amplitude Variation with Offset (AVO) for elastic impedance inversion (e.g. Aki and Richards, 1980; Li et al., 2003; Ruger, 1997). Figures 1 and 2 show results of AVO analysis and simultaneous inversion at the Mississippian and Arbuckle reservoirs. This research provides a comprehensive assessment of seismic attribute analysis for characterization of two important mid-continent carbonate reservoirs which are of primary interest to KICC membership.

Key Findings

- High porosity zones in the Mississippian and the Arbuckle Group exhibit characteristic AVO response
- AVO classification can be employed to identify the porous zones at Wellington Field 3D volume using the intercept-gradient cross plotting technique
- Simultaneous AVO impedance inversion results in improved estimation of Mississippian reservoir and the Arbuckle Group properties than model-based inversion of post-stack data
- Flow units in the Arbuckle can be mapped using AVO analysis and Simultaneous AVO impedance inversion

Deliverables

i) Comprehensive assessment of *pre-stack* seismic attribute analysis for Mississippian and Arbuckle reservoir characterization

ii) Evaluation of AVO *pre-stack* seismic gather analysis methods for mid-continent carbonate reservoir property prediction

iii) Acoustic and elastic impedance inversion volumes and predicted reservoir porosity and density maps

iv) Evaluation of seismic methods for identification of flow units in carbonate reservoirs

v) *Post-* and *pre-stack* seismic analysis workflows for Mississippian and Arbuckle reservoirs

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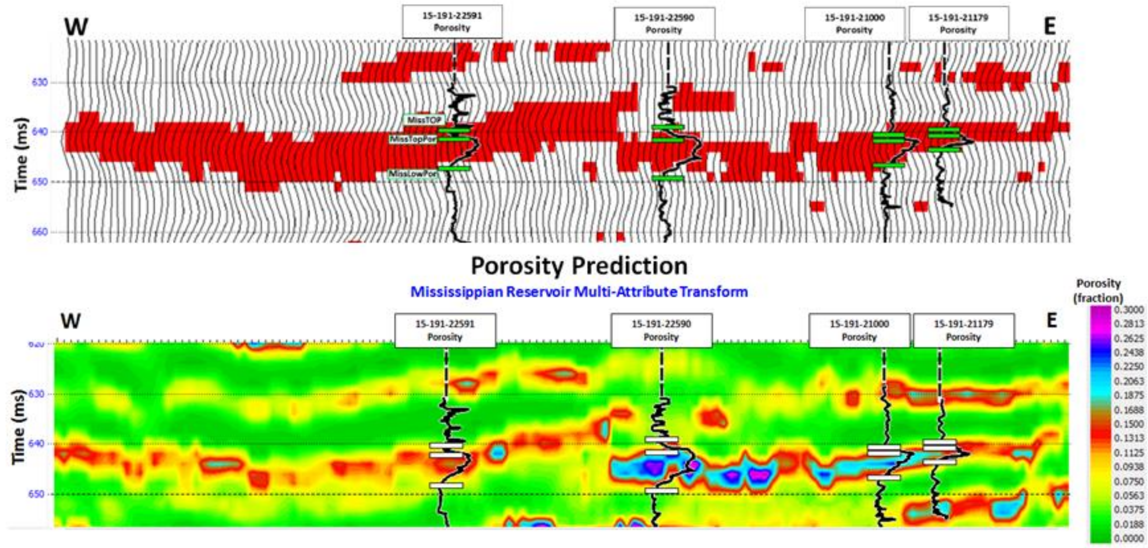

Figure 1. *(upper) AVO highlighted zones (red color) on seismic data displayed along with porosity logs at the Mississippian reservoir. AVO analysis identifies the Mississippian reservoir which has thickness below seismic resolution. (lower) Seismic prediction of reservoir porosity shown along with porosity logs.*

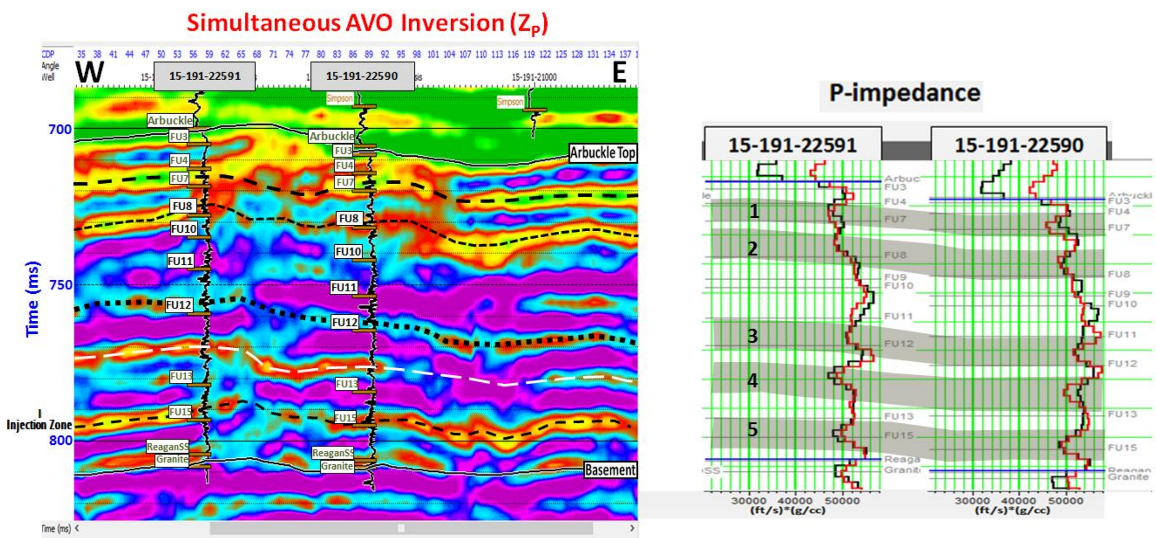

Figure 2. *(left) Simultaneous AVO inverted P-wave impedance (Z_P) cross section. Five low impedance zones are identified by the dashed lines. (right) Measured P-impedance logs (Black) from wells #15-121-22590 and #15-121-22591, and the inverted P-impedance traces (Red) at the two well locations. Five distinct low impedance zones are shaded in grey and coincide with flow units idenfied in well data.*

Seismic Attribute Analysis of the Arbuckle Group from 3D-3C Data at Cutter Field, Southwest Kansas

George Tsoflias, Lynn Watney, Clyde Redger

SUBSURFACE APPLICATION: Seismic imaging the Arbuckle Group. Assessment of three dimensional, three component imaging and utility of seismic attribute analysis.
STATUS: Project completed and not yet published
TIMING: Significant results to be reported – Results currently available to membership
FUNDING: Partial from United States Department of Energy

Purpose

Arbuckle Group reservoirs boast a rich history of oil production and have potential to store vast quantities of captured carbon dioxide (Franseen et al., 2004). Carbonate reservoirs, analogous to the Arbuckle Group, can be challenging to characterize with seismic methods due to a number of geophysical challenges including poor reflectivity, scattering of energy by karst, and heterogeneous rock properties. This study investigates the utility of attributes extracted from 3D-3C seismic data (Stewart et al., 2003) for predicting rock properties within the Arbuckle Group at southwest Kansas. Results from this study have implications for future seismic investigations of the Arbuckle Group and analogous carbonate reservoirs.

Project Description

Cutter Field is located within the Hugoton embayment of the Anadarko basin. The Cutter Field data set includes ~25 km^2 of post-stack 3D-3C data and a single well, Cutter KGS 1, which was drilled to basement in 2012. The upper contact of the Arbuckle Group is not visible in the P-P or P-SV data due to insufficient contrast in elastic properties between the Arbuckle Group and the overlying Viola Limestone. The base contact between the Arbuckle Group and the underlying Gunter Sandstone can be traced in the P-P data across a majority of the survey area. Internal reflections occur within the Arbuckle Group but are highly discontinuous. Karst collapse features are clearly recognizable in the P-P data and appear to originate near the top of the Arbuckle Group (Figure 1). The P-SV data quality appears to be comparable to that of the P-P data for depths less than 1500 m, but far less than that of the P-P data at Arbuckle Group depth.

P-impedance inversion results show the three P-impedance layers within the Arbuckle Group: (1) a high P-impedance layer in the upper Arbuckle, (2) a low P-impedance layer in the middle Arbuckle, and (3) a high P-impedance layer in the lower Arbuckle. The three layers are laterally extensive but not uniform. The lack of uniformity explains, at least partially, the occurrence of discontinuous reflections within the Arbuckle Group. Arbuckle Group flow units interpreted by Gerlach (2014) appear to coincide with P-impedance layers, suggesting that flow unit boundaries may be related to P-impedance boundaries.

Key Findings

- A strong correlation is evident between Arbuckle Group neutron porosity and P-impedance

- P-impedance inversion and well log data suggest that P-impedance, and perhaps flow units, within the Arbuckle Group can be approximated by a three-layer model
- Karst collapse features are clearly evident in the seismic data
- P-SV data quality is poor at Arbuckle Group depth and is not useful for quantitative interpretation

Deliverables

i) Comprehensive assessment of *post-stack* seismic attribute analysis of P-P and converted P-SV for Arbuckle reservoir characterization

ii) Detailed mapping of Arbuckle structures, faults and karst collapse features

iii) P-impedance inversion volume

iv) MS Thesis, Redger C. (2015) Seismic Attribute Analysis of the Upper Morrow Sandstone and the Arbuckle Group from 3D-3C Seismic Data at Cutter Field, Southwest Kansas

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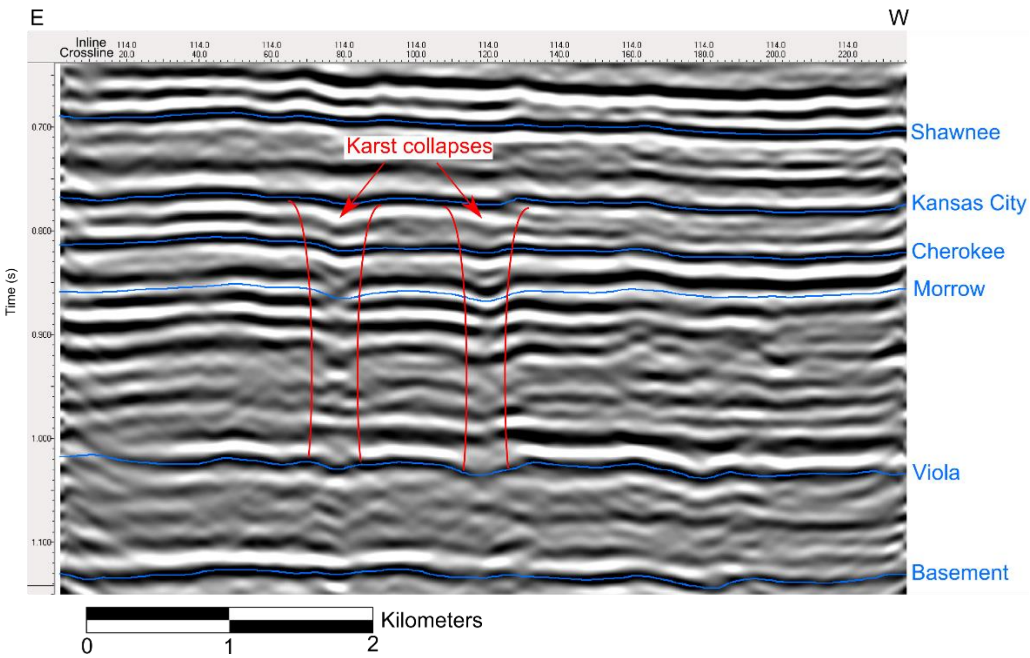

Figure 1. *Seismic profile showing karst collapse features in the Cutter 3D-3C survey. The karst collapse features appear to originate near the top of the Arbuckle Group, which is located directly beneath the Viola horizon.*

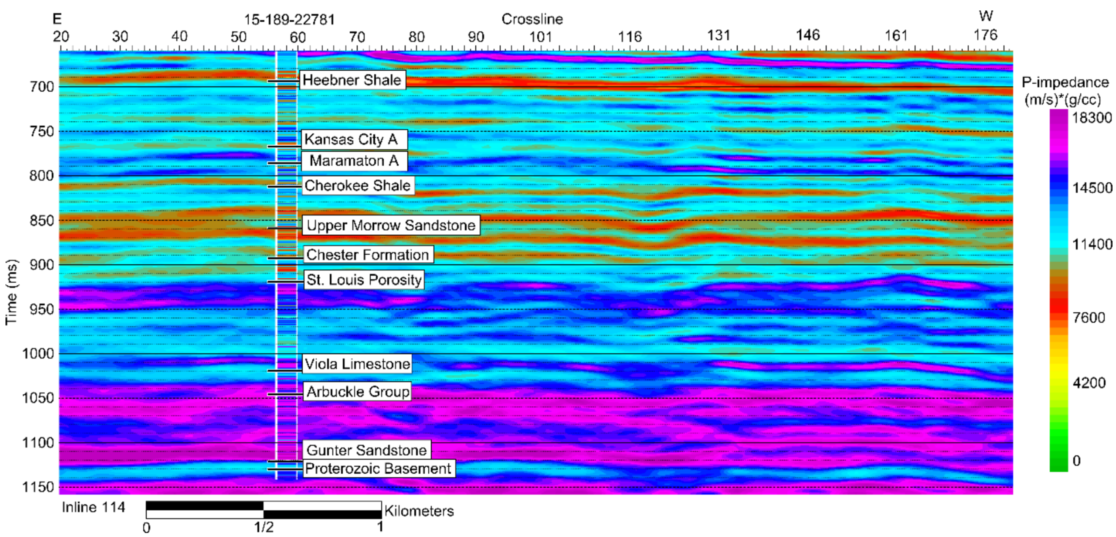

Figure 2. *Inverted P-impedance profile with inserted P-impedance log from well Cutter KGS 1 (API: 15-189-22781). The inverted volume lacks the resolution of the well log, but provides an accurate low-frequency approximation of P-impedance. Three P-impedance layers are evident within the Arbuckle Group.*

Seismic Anisotropy Investigation and Fracture Characterization in the Mississippian and Arbuckle Reservoirs, South-Central Kansas

George Tsoflias, Brandon Graham, Lynn Watney

SUBSURFACE APPLICATION: Determination of Mississippian and Arbuckle reservoir seismic anisotropy and characterization of fractures using 3D seismic reflection data
STATUS: Long-term project in progress
TIMING: Significant results to be reported to membership
FUNDING: Partial from United States Department of Energy

Purpose

The Mississippian Lime play in the US mid-continent has been a major hydrocarbon producer and is a target for enhanced oil recovery operations. The Lower Ordovician Arbuckle Group dolomite is a saline aquifer with significant potential for CO_2 storage. However, carbonate reservoirs are heterogeneous and the distribution of properties controlling the flow of fluids is often below seismic resolution. Ongoing KICC seismic analysis research identified characteristic relationships between Mississippian and Arbuckle properties (thickness, porosity) and seismic attributes (Amplitude Variation with Offset – AVO, P- and S-Impedance), and developed seismic inverse workflows that predict accurately porosity distribution and flow units at Wellington field. This research expands this newly acquired understanding of carbonate rock elastic properties at Wellington field to quantify stress distribution, fracture orientation and density, and help understand subsurface geomechanical properties with implications in rock fracturing, CO_2 EOR and sequestration, and water injection.

Project Description

This study focuses on azimuthal seismic anisotropy to visualize reservoir stress and fractures. Seismic anisotropy is observed as the variation in seismic velocity and amplitude with orientation of wave propagation (Aki and Richards, 1980). We use 3D seismic data in the pre-stack azimuth domain (AVAZ) to quantify Mississippian and Arbuckle seismic anisotropy and infer fracture properties (orientation and density) at the Wellington Field in South-Central Kansas. We consider vertical planes of isotropy due to stress and vertical fractures referred as Horizontal Transverse Isotropy (HTI) or Azimuthal Anisotropy (Ruger, 1998; Thomsen, 2002; Lynn, 2016).

Key Findings

- Mississippian and Arbuckle anisotropic fabric is along and orthogonal to regional maximum horizontal stress (~70-80 degrees) and with the main structural feature in the field, a NE trending fault mapped in 3D seismic (figure 1)
- Seismic anisotropy observations are in agreement with natural fracture sets observed in borehole Formation Micro Imaging (FMI) logs, dipole-dipole sonic logs, regional fault maps, and regional earthquake focal mechanism analysis (Schwab, 2016)
- Anisotropy analysis using 3D surface seismic data is shown to be a suitable method for predicting stress field orientation and estimating fracture geometries in the Mississippian and Arbuckle reservoirs

Deliverables

i) Evaluation of AVAZ seismic anisotropy analysis methods for Mississippian and Arbuckle reservoir property prediction
ii) Development of workflows for AVAZ analysis in the US midcontinent carbonate reservoirs
iii) Wellington field seismic anisotropy analysis correlated to well data, regional tectonic and seismicity studies

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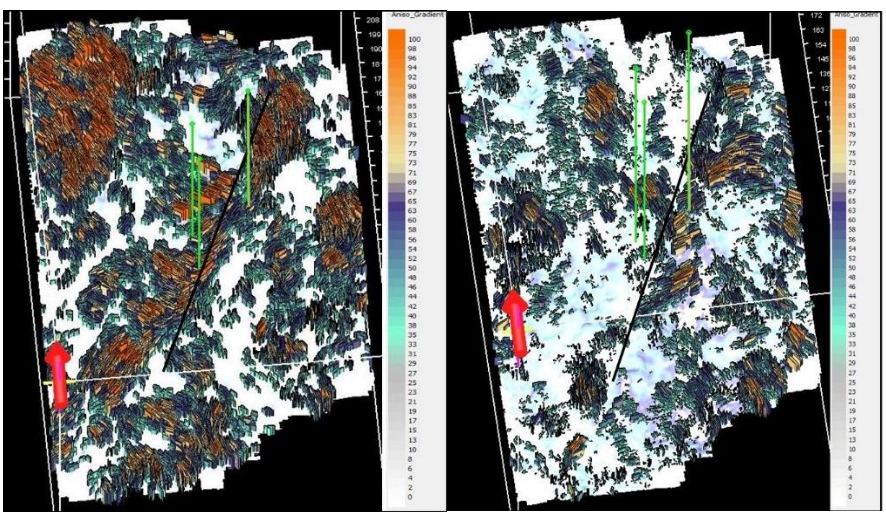

Figure 1. *Tilted perspective of the azimuthal planes of isotropy at the Mississippian reservoir (anisotropy gradient 33%-100% in color) (left) and the Arbuckle (anisotropy gradient 25%-100% in color) (right). The orientation can be interpreted as fractures and stress direction, and the size and color is the degree of anisotropy. The black line delineates a fault mapped in the 3D seismic. Wells KGS# 1-32, 2-32 and 1-28 are sown in green (from left to right).*

Seismic Stratigraphic Architecture and Geomorphology: Cenozoic Isolated Carbonate Platforms Systems

Gene Rankey, Tom Neal, Bill Mynatt, Michael Poppelreiter, SEACaRL collaborators

SUBSURFACE APPLICATION: Understanding the 3D architecture of isolated carbonate platforms and shelves, most directly related to Cenozoic systems, including Southeast Asia and parts of the Middle East.
STATUS: Long-term project in progress
TIMING: Results soon available to membership; Phase 2 starting
FUNDING: Partly funded. Seeking additional funding and data

Objective and Relevance to Sponsors

An important key to unraveling the architecture of subsurface isolated carbonate platforms is identifying and mapping seismic stratigraphic variations. Stratal terminations, superposition and seismic geometries commonly reveal an architecture of platforms that is quite distinct from carbonate ramps and rimmed shelves. Rather than being homogeneous and isotropic, many isolated carbonate platform reservoirs include variable internal heterogeneity and complex geometric relations with off-platform strata on their flanks. The purpose of this project is to ***characterize the nature and controls on stratigraphic architecture of isolated carbonate platforms***. Focus initially will be on the Miocene of Southeast Asia and Northwest Shelf, Australia, with the general goal of unraveling qualitative and quantitative trends in patterns of growth that provide predictive insights for understanding the nature and controls on stratal heterogeneity of isolated platforms.

Background

The Central Luconia Province of offshore Sarawak, Malaysia (South China Sea) is a particularly well-endowed region that includes more than 200 carbonate buildups of Oligocene to Recent age. During the Middle Miocene, a general relative rise in sea level and decreased rate of siliciclastic influx to Central Luconia led to initiation of carbonate sedimentation. Early publications on these buildups (most notably the seminal paper of Epting, 1980) described much of the essence of the stratigraphy of the buildups, by reference to various stages of development. These stages include build-out (rate of carbonate production and accumulation greater than rate of sea-level rise), build-up (rate of carbonate accumulation similar to rate of sea-level rise), and build-in (rate of production and accumulation less than the rate of sea-level rise), the latter including a backstepping stage and a drowning stage. The area represents a natural laboratory to explore a range of isolated platform systems, in part because many buildups form proved hydrocarbon reservoirs, and thus have a wealth of data across a range of settings.

Project Description

In this context, the purpose of this project is to describe details of the seismic stratigraphic architecture of Middle to Upper Miocene isolated carbonate buildups of Central Luconia and their interactions with adjacent siliciclastic strata. Working with collaborators at Southeast Asia Carbonate Research Laboratory (SEACaRL) at the Universiti Teknologi

PETRONAS (UTP), the long-term project will integrate seismic observations with well log and core data to develop conceptual and numerical models for the nature and controls on their heterogeneity.

A recently completed study (presentated at KICC in 2019) integrated seismic data, two cores, and well log suites of one platform, providing the basis for interpreting its seismic stratigraphy and architecture, and evaluating controls on its growth and demise. Results (e.g., Figure 1) reveal that although indeed many parts of the platform appear to have broadly tabular geometry, syndepositional structural deformation and interaction with adjacent basinal siliciclastics created complex geometries near the margins and flanks of the buildup throughout its evolution. Nonetheless, backstepping is the dominant stratigraphic motif, and the platforms ultimately drown.

Phase 2 of this study will include comparison with other isolated platforms in Central Luconia, and integration of the seismic data with core and log data. We expect the data to reveal that although the detailed stratigraphic record of each platform is shaped by local and regional contingencies (timing of siliciclastic influx, structural deformation), patterns and trends among platforms are evident. These patterns represent predictive motifs. Numerical modeling of these platforms ultimately will provide a means to explicitly test scenarios related to physical, chemical, and biological influences.

In marked contrast to the backstepping and aggrading motifs evident in many Central Luconia region, interpretations suggest that at least some of the Miocene platforms of the Northwest Shelf of Australia are aggradational to highly progradational (e.g., Figure 2). These platforms will be described systematically to provide a contrast with the Malaysian examples; preliminary results were presented at KICC in 2019. Comparison among areas should provide insights into controls on platform evolution and geometry.

Expected Results and Deliverables

This study will characterize and quantify depositional architecture in several seismic data sets. Results will include maps and images and databases on quantitative seismic geomorphometric attributes, presented at the annual meeting, in theses of students available to sponsors, and in publications. The qualitative and quantitative pattern analyses represent a means to explore "first order" stratigraphic principles governing the accumulation of contrasting styles of seismic stratigraphy and internal heterogeneity of isolated carbonate platforms.

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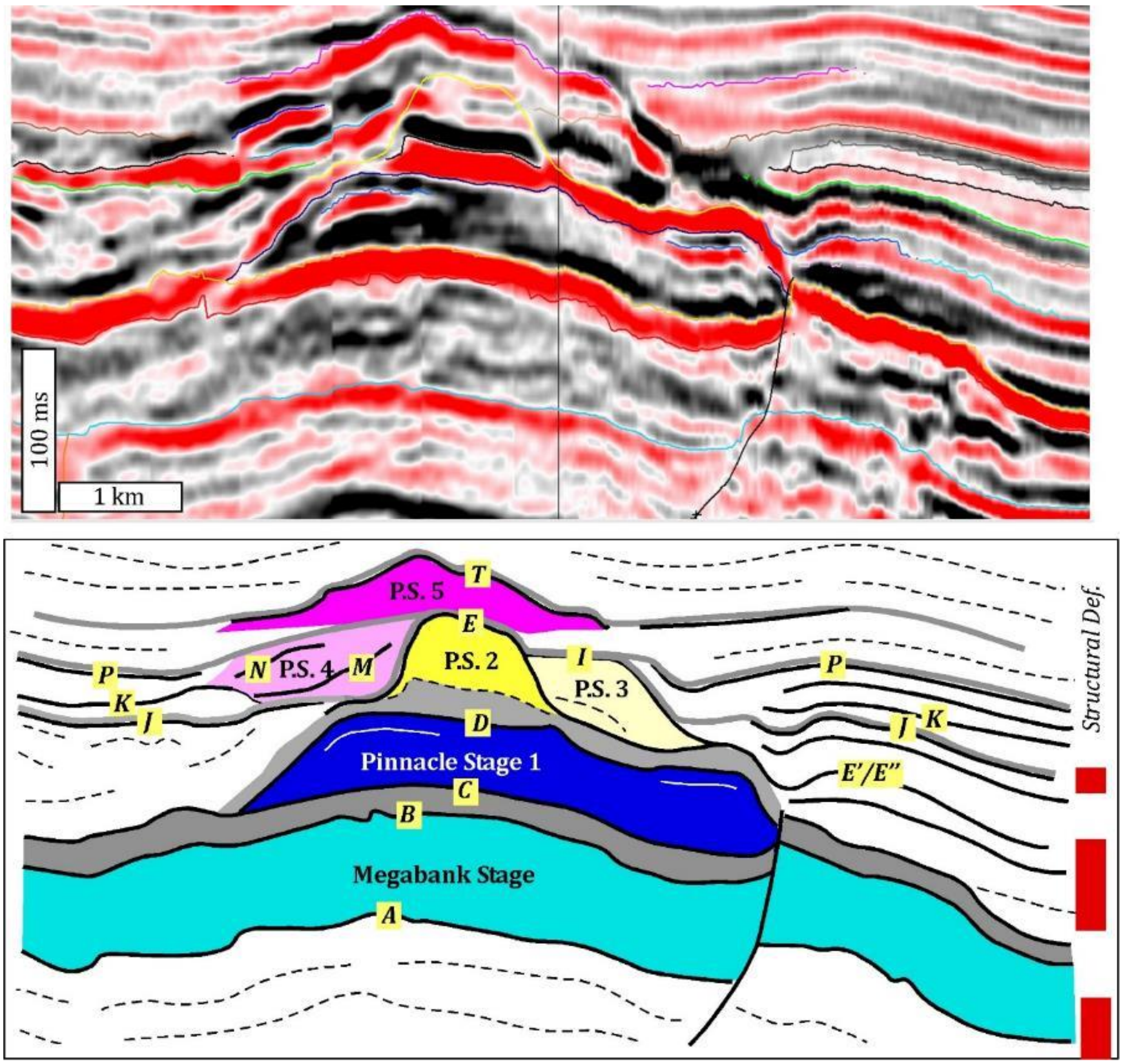

Figure 1. *Summary of geometric evolution of field EX. A) Arbitrary, quadrature-phase seismic line with interpreted seismic horizons. B) Interpretive representation of line in part A, illustrating the various pinnacle stages. Grey colored intervals are interpreted transgressive stages. Some of these are comparable to build-in phases of Epting (1980), others are defined based on downlaps. Red bars represent are intervals of interpreted structural deformation.*

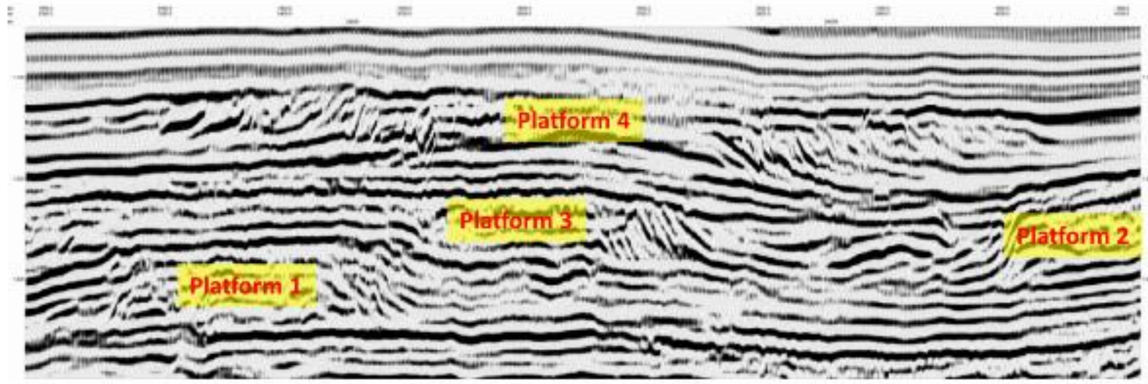

***Figure 2**. Illustrative seismic line from a 3D volume of the Northwest Australia Shelf. This line shows parts of four platforms (intersected at various orientations). Note how these are aggradational to slightly progradational (lower three) to highly progradational (Platform 4), patterns which contrast with the aggradational to retrogradational patterns illustrated in many Central Luconia platforms (e.g., Figure 1).*

Seismic Modeling of Geological Heterogeneity and Expression of Isolated Platforms

Adrienne Duarte and Gene Rankey

SUBSURFACE APPLICATION: This project explores how geologic heterogeneity impacts the seismic character of isolated platforms. Insights will be applicable to both exploration and development settings for more refined and accurate interpretation of seismic data of isolated platform reservoirs
STATUS: Focused-term project recently completed
TIMING: Duarte's thesis recently completed
FUNDING: Funded

Purpose

Isolated carbonate platforms, the iconic carbonate geomorphic setting, include many important hydrocarbon reservoirs (e.g., Devonian, Western Canadian Basin and Cenozoic, Southeast Asia) (Bachtel et al., 2004; Burgess et al., 2013; Watts et al. 1994). Variability in facies (size, distribution, and stacking patterns) and diagenesis (and therefore porosity) across isolated platforms pose a challenge for predicting geologic heterogeneity from seismic data (Masaferro et al., 2004; Burgess et al., 2013). To test the hypothesis that geologic heterogeneity creates a statistically discernable impact on seismic character of isolated carbonate platforms, this project will develop quantitative understanding of this relationship by generating ***synthetic seismic models of isolated carbonate platforms where geologic heterogeneity can be systematically isolated and varied – and its impact evaluated.*** Unlike other studies that model one specific outcrop or reservoir, however, this project will systematically and numerically model a range of geologic variables that impact platforms throughout the geologic record.

Project Description

The project will explore how comparable variability in subsurface analogs might be recognized from seismic data. The data of variability in Holocene facies morphometrics (spatial patterns; see Rankey, 2016) coupled with stratigraphic (vertical patterns) and petrophysical (rock property) information from subsurface systems provide fundamental input for construction of a suite of seismic forward models. These models have been queried qualitatively (seismic geometries) and quantitatively (seismic attributes) and compared with the controlled inputs to explore fundamental geologic controls on seismic expression of isolated carbonate platforms.

To explore the role of geologic variability on seismic character of isolated carbonate platforms, this project focuses on several objectives:

1) *Understand "end-member" geologic analogs* by describing geologic variability in core from Devonian Nisku pinnacles (low porosity, greenhouse) and a Miocene South China Sea platform (high porosity, icehouse). This step will use published and new data to provide geologic perspectives on important parameters such as vertical stratigraphic heterogeneities within isolated carbonate platforms.

2) *Construct a suite of idealized geologic models* in Petrel to analytically capture an array of geologic variability. These simplified platforms are constrained to four facies belts (slope, reef, reef sand apron, and platform interior), but may include features such as patch or pinnacle reefs. Facies distribution will be based on a range of facies probabilities from modern analogs from the South China Sea (see Rankey, 2016). Several facies stacking patterns (e.g., prograding, aggrading, and backstepping), with and without low-porosity layers, provide a basis for creating the facies volume, which can then be stochastically populated with facies-based porosity (and then, velocity and density). The means and ranges of porosity will be based upon Devonian (porosity between 3% and 16%) and Miocene (high between 16% and 36%) analogs (Watts et al., 1994; Fournier and Borgomano 2007), and converted to velocity using published data (e.g., Eberli et al., 2003). Upon completion, the geologic models will include velocity and density (impedance) in a three-dimensional volume.
3) *Generate synthetic seismic models* (e.g., Figure 1) from the geologic models by convolving the impedance volume with seismic pulses of various frequencies.
4) *Extract seismic attributes* from seismic data. Attributes characterize data in individual traces (e.g., amplitude, frequency, phase), or characterize the relationship among adjacent traces (e.g., dip, coherence). A suite of attributes should capture the variability in seismic character.
5) *Understand geological controls on seismic character* by comparing seismic attributes with the known (modeled) geologic variability, using multiple linear regression or other statistical techniques, as appropriate.

Deliverables

The primary results of the study will include qualitative understanding of how differences in facies size, distribution, and stacking patterns of isolated platforms throughout geologic history may have changed their seismic character. Beyond qualitative assessment, quantitative analysis will reveal how this geological heterogeneity would be reflected in seismic data and lead to objectively discernable changes in seismic character. The final results will be reported in the thesis of Duarte and associated publication.

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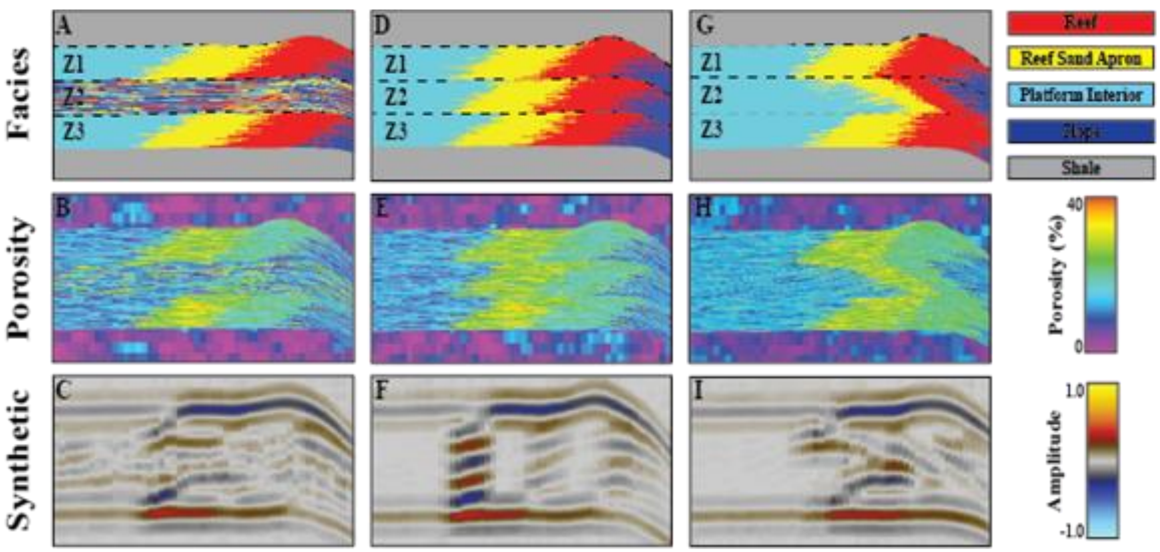

***Figure 1**. Matrix of representative geologic, models (top row), porosity models (middle row), and synthetic volumes (bottom row) at a scale of < 1 seismic loop per reservoir zone. Black dashed lines separate reservoir zones; zone Z2 is the focus. In each model, porosity and impedance were distributed by Sequential Gaussian Simulation with a high standard deviation. A-C) Facies (A) porosity (B) and synthetic seismic (C) models of the stochastically populated scenario. D-F) Facies (D) porosity (E) and synthetic seismic (F) models of the aggradational facies stacking pattern scenario. G-F) Facies (G) porosity (H) and synthetic seismic (I) models of the interiorward-prograding scenario. Note that different geologic input can yield qualitatively similar seismic reflection patterns (i.e. inclined high amplitude reflectors).*

3-D Imaging of Facies and Porosity in Microbial Carbonates of the Messinian of Spain Using GPR

Robert H. Goldstein, Evan K. Franseen, George Tsoflias, and Katharine Knoph

SUBSURFACE APPLICATION: Useful analog for 3-D modeling of porosity in microbialite reservoirs such as pre-salt Brazil, offshore Angola, Jurassic Smackover, Arbuckle/Ellenburger
STATUS: Long-term project in progress
TIMING: Significant results to be reported – Results currently available to membership
FUNDING: Partial funding

Purpose

Understanding how facies and porosity are generated in thin topography-draping sequences can have significant impact to refining carbonate sequence stratigraphic models. This study will resolve 3-D geometries of oolite-microbialite-reef sequences and porosity by combining geologic and high-resolution GPR data from well-exposed parts of the Terminal Carbonate Complex (TCC) in SE Spain. Comprehensive 3-D models created in Petrel from the integration of GPR data with 3-D stratigraphic models will contribute to process-response models of facies and porosity within thin, topography-draping carbonate sequences.

Project Description

Outcrop studies complemented by geophysical imaging can explore variations in depositional and diagenetic character of carbonate systems in three dimensions. The Terminal Carbonate Complex (TCC) of the Miocene of SE Spain is one succession where paleotopography and sea-level history are well documented (Franseen et al., 1998). Exposures contain four carbonate sequences that drape preserved paleotopography, deposited in association with high-amplitude, high-frequency glacioeustatic change (Figure 1) (Lipinski, 2009). The surface onto which the TCC was deposited at La Molata has been documented to lie at an intermediate elevation between regional sea-level highstand and lowstand positions (Lipinski, 2009). Evaluation of stratal geometry, facies, and porosity distribution within this 3-D framework facilitates understanding the response of these systems to sea-level change. Additionally, the stratigraphic patterns of the oolite-microbialite-reef sequences of the TCC are of great interest because many highly productive reservoirs are composed of microbialites and oolites deposited in similar settings (Franseen et al., 2007).

GPR imaging has been used for determining facies architecture and porosity distribution in carbonate systems (Grasmueck and Weger, 2002; Franseen et al., 2007; Neal et al., 2008; Tsoflias, 2008). GPR data coupled with 3-D stratigraphic modeling, has potential to enhance understanding of patterns of sedimentation and porosity as they relate to changes in sea level and paleotopography. A preliminary survey in the area (Figure 2) showed that GPR reflections correspond to geometries associated with sedimentologic and stratigraphic features that can be calibrated to well-documented outcrops. It is expected that areas and patterns of elevated porosity will be discernable from the GPR data based on associated dielectric constant contrasts creating reflective interfaces and changes in radar wave velocity of propagation.

To determine the 3-D facies architecture, high-resolution GPR data will be integrated with detailed stratigraphic data to create 3-D models that portray the distribution of stratigraphic variability within the TCC. Densely-spaced 3-D grids of GPR data will be acquired at locations of differing paleotopographies. The integration of 3-D GPR and outcrop data has potential to illustrate facies and porosity of thrombolite and oolite facies in the context of their paleotopography and sea-level history. Relating distribution of these attributes to paleotopography can refine process-response models for the timing and paleotopographic controls on thrombolite and oolite deposition and diagenesis.

Deliverables

This study will enhance process-response models of facies and porosity of thin topography-draping sequences, as well as provide insights for the controls on thrombolitic and oolitic deposits. Furthermore, the 3-D models of facies geometries and distributions and their response to changes in sea level and paleotopography will provide conceptual and quantitative models that could be applied to improve exploration and exploitation in analogous carbonate reservoirs.

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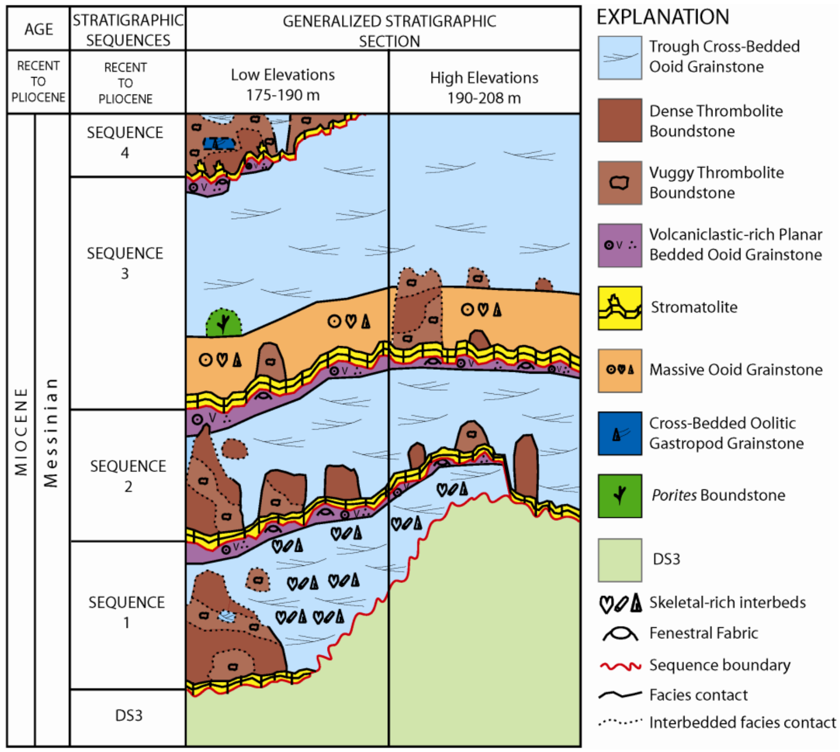

Figure 1. *General stratigraphic sections of the TCC of La Molata displaying the distribution of lithofacies in relation to paleotopographic elevation (from Lipinski, 2009).*

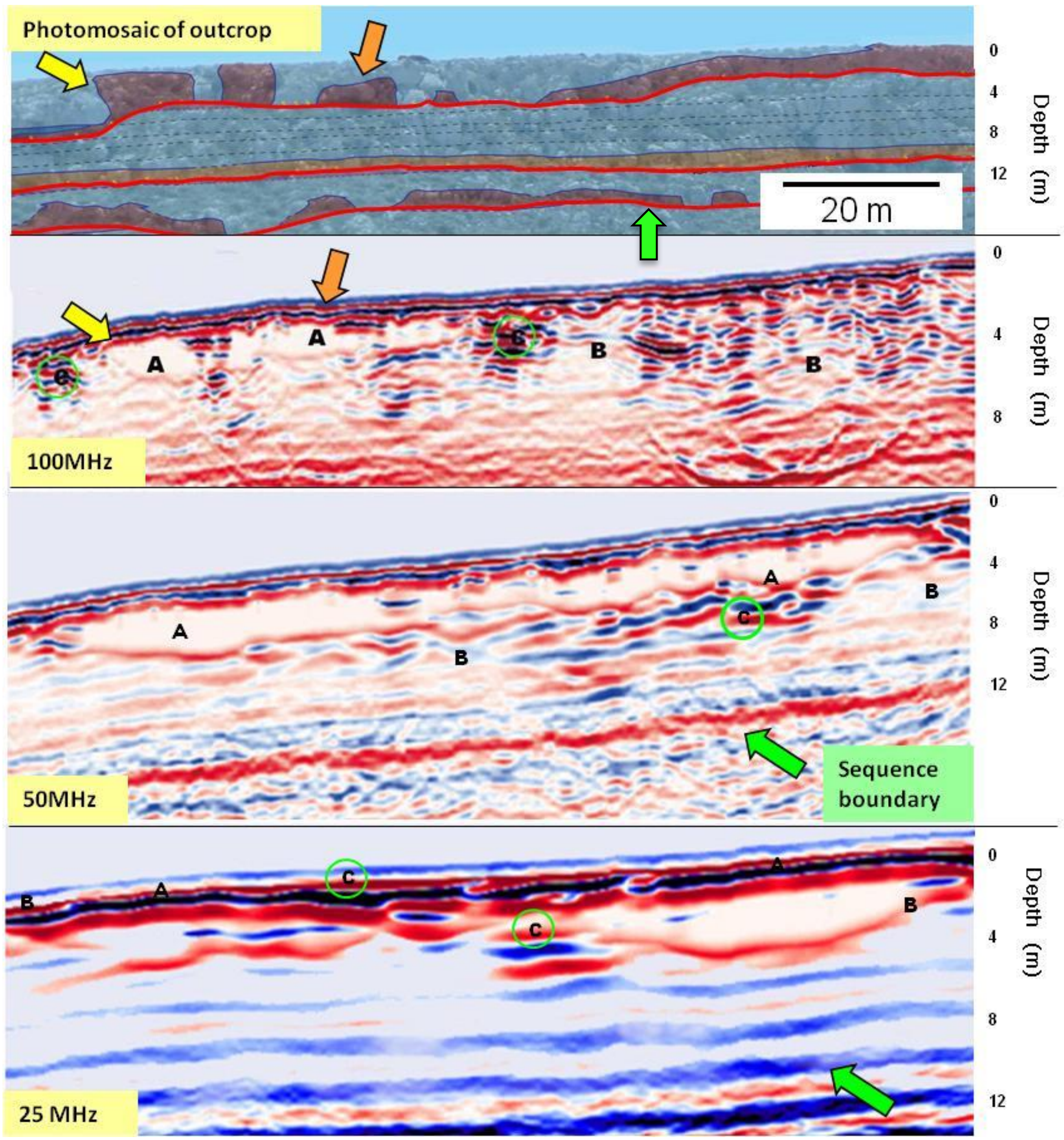

Figure 2*: Outcrop photomosaic (Lipinski, 2009) shown at top of figure and corresponding GPR profiles of all three frequencies with radar facies labeled (A, B, C-with green circles). The photomosaic is highlighted with different colors to emphasize varying lithologies (Brown = thrombolite, light blue = oolite. The individual thrombolite bodies shown in brown color correspond closely with GPR Facies A (very low porosity- tight thrombolite) in the 100 MHz profile. Yellow and orange arrows show thrombolite bodies that appear to change morphology a small amount between the outcrop face and 2 m to the interior where the GPR profile was collected. The 50 and 25 MHz profiles offer lower resolution than the 100 MHz data, but are capable of penetrating deeper and imaging larger-scale features, such as sequence boundaries (e.g., prominent reflector (green arrow) at 12 m depth on 25 and 50 MHz profiles.*

Controls on Facies Distribution and Architecture of Holocene Carbonates

Holocene systems offer the unique opportunity to explore, explicitly compare, and rigorously quantify and test process-response linkages in carbonate depositional systems and to explore and qualify map-view patterns in facies and granulometric attributes. Geochemical, physical, climate, nutrient, and biological controls can also be explored to enhance predictability in both marine and lacustrine systems. Examples of some current and pending projects include:

Investigating microbial and geochemical influences on microbialite formation

Jennifer Roberts, Bryan Rodriguez-Colon, Belinda Sturm, Gregory Baker

SUBSURFACE APPLICATION: Modeling spatial variability of microbialite carbonate reservoirs.
PROPOSED WORK: April 2019–May 2020
TIMING: Proposed fieldwork and analyses
FUNDING: KICC seed funding.

Purpose

Lacustrine microbialite systems, such as the pre-salt system of Brazil, can be productive reservoirs. Yet microbialite formations are also spatially heterogeneous (Harris et al., 2013), and their genesis and subsequent preservation are not well-constrained, even as their variability has been documented (e.g. Della Porta, 2015). Moreover, although modern microbial mats are known to produce microbialites through binding and mineralization (Burne and Moore, 1987), geochemical and microbiological influences on mat morphology (which impact porosity; e.g., Dupraz et al., 2014; 2011), as well as the mineralization of these features, are not fully understood.

Here we propose a comparative study of two modern (<500 years old) salterns in southwest Puerto Rico, with microbialites associated with vital microbial mats occurring in only one of the two salterns. Though separated by only five meters, one saltern contains a macro-structure of mats and resulting microbialites that are stromatolitic, with obvious stromatolite "heads" that have developed, whereas in the adjacent saltern of similar size and shape only flat-lying, laminated mats are present.

The goal of this work is to use this unique occurrence and opportunity for comparative analysis to investigate geochemical and microbiological influences on microbialite formation, which are presumed (e.g. Riding, 2000), but have not yet been mechanistically linked. We will also use small unmanned aircraft systems (sUAS) and photogrammetric structure from motion analysis (SfM) to map the occurrence and spatial distribution of the microbialites. ***Our broad aim is to identify parameters that control pore structure and preservation, as well as spatial variation, in microbialite growth and architecture.*** Such findings hold the potential to inform future predictions of microbialite textures and porosity as a function of mat biogeochemistry, as well as modeling of spatial heterogeneity in microbialite carbonate reservoirs.

Results from Previous Work

A number of abandoned salterns dating to ~500 years before present exist on the southwestern shore of Puerto Rico, near Guánica (Figure 1a). Samples were taken from the pond with stromatolitic textures in July 2018 and December 2018; to-date, adjacent ponds have not been sampled or otherwise studied. Satellite images demonstrate that the stromatolitic morphology (Figure 1d, e) has been present in this saltern of interest (Figure 1b, c) since at least 2006, while adjacent ponds do not appear to have these morphologies in satellite images nor were they observed in the field. Photomicrographs of the mats demonstrate bound allochthonous grains as well as pore-filling precipitates (Figure 1f). X-ray diffraction analysis of sediments (XRD) reveals the mineralogy to be comprised of Mg-calcite and aragonite. Preliminary characterization of the microbial mat communities reveals a consortium of photosynthetic algae and bacteria, abundant bacterial groups related to sulfur metabolism, and methanogens, suggesting persistent anoxic conditions locally and perhaps even more broadly.

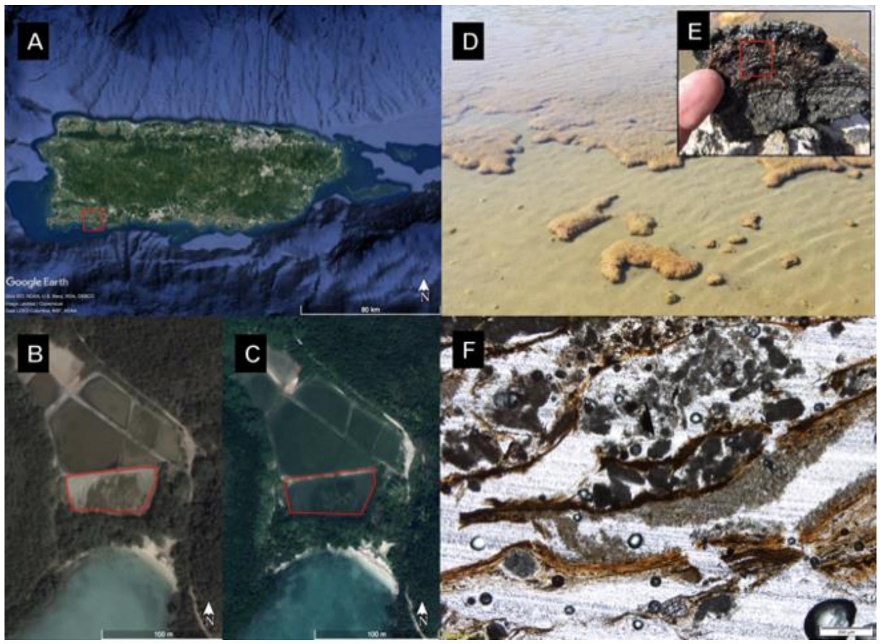

Figure 1. *a. Location of abandoned salterns near Guánica, Puerto Rico. b. Google Earth images of the saltern containing stromatolitic mounds demonstrate this site experiences noticeable water level changes during dry season and c. wet season. d. Stromatolitic mounds were observed throughout the small saltern, and e. demonstrate living layered microbial communities. f. Photomicrograph of thin-section under transmitted light shows the presence of authigenic mineral precipitates within the expolymeric substances, which also encase trapped allochthonous sediment. Scale bar=200 μm.*

Proposed Project Description

Field Characterization and Sampling

We propose a comprehensive field sampling trip to a) collect high-resolution aerial photography via small unmanned aircraft systems (sUAS) of two identified salterns of interest, adjacent salterns, and other saline ponds in the vicinity (Figure 2), and b) conduct detailed sampling of salterns and ponds for microbiological, geochemical, and mineralogic analyses. We will collect surface sediment, mat, and fluid samples across transects of the salterns, which will include the saltern containing stromatolitic bodies, the adjacent pond to its north, and any other pond that is of interest after reconnaissance. For the saltern containing microbialites, we will collect sediment and mat core samples across similar transects to a depth of ~1 m. Local water wells will be located and sampled, and where possible temporary piezometers will be installed to access groundwater local to the salterns and ponds.

Deliverables

This project will provide new understanding of the spatial distribution of stromatolitic bodies, linked with detailed textural, mineralogic, geochemical, and microbiolgical datasets, and analyzed in comparison to similar environments that do not develop stromatolitic textures. Taken together, these data will provide a comprehensive and, we expect, mechanistic approach to understanding a) the formation of stromatolitic mats and b) parameters that influence their mineralization. Specific deliverables include: presentations at meetings including the 2019 AbSciCon, 2019 Geobiology Society Conference, 2019 GSA Annual Meeting, and 2020 KICC Annual Meeting, as well as a completed MS thesis by Bryan Rodriguez-Colon, which will be provided to sponsors through the KICC website. Marissa Duckett, an undergraduate biology student working on this project, will also produce an abstract for KU's Undergraduate Research Symposium. Following this work, we expect to submit a proposal to expand our research and findings through funding from the NSF Geobiology and Low Temperature Geochemistry program, the results of which will also be available to KICC sponsors.

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Sediment Dynamics and Geomorphology of a Southeast Asia Isolated Platform: Holocene Layang-Layang Atoll, Malaysia, South China Sea

Thomas Neal, Gene Rankey, and Kim Jakobsen

SUBSURFACE APPLICATION: Numerous reservoirs are from ancient isolated carbonate platforms, including the Miocene of Southeast Asia, Tengiz and other platforms of the former Soviet Union, Devonian of western Canadian Basin, and Silurian of the Michigan and Illinois basins. This system can provide insights and analogues to these ancient reservoirs, but especially for similar Cenozoic coral-algal reef reservoirs of Southeast Asia.
STATUS: Part of a long-term project in progress
TIMING: In progress, with final report expected by mid-2020
FUNDING: Fully funded

Purpose

Isolated carbonate platforms are common in the geologic record range from the Paleozoic, Mesozoic and Cenozoic, and can include productive hydrocarbon reservoirs. Although the general stratigraphy and depositional facies of these ancient platforms are well known, details of the controls, patterns, and variability of sediment accumulations are less well constrained. Recent regional studies of the South China Sea show the significance of oceanographic processes on the distribution and extent of carbonate platform geomorphic elements - shelf-marginal reefs, patch reefs, reef sand aprons and lagoons (Rankey and Garza-Perez 2012; Rankey 2016). To develop more ***rigorous predictive conceptual models for carbonate platform sedimentation and their hydrodynamic controls***, this study characterizes and numerically models a Holocene atoll offshore Sabah, Malaysia. Better understanding of oceanographic and sedimentary processes controlling isolated carbonate platforms can improve conceptual models of variability in analogous reservoirs.

Project Description

The focus of research is on the atoll of Pulau Layang-Layang which lies 280 km off the north coast of Malaysian Borneo. Located in the equatorial region within the Spratly Island area of the South China Sea, the isolated carbonate platform rises up nearly 1000 m from the surrounding deep ocean. The atoll is ~7 by 2 km, with the long axis trending east - west. Major geomorphic elements include the reef, reef sand apron, patch reefs, and lagoon (Figure 1A). The reef lies near sea level, exposed only during spring low tide. The reef sand apron asymmetrically fringes inside the reef widest (up to 1.5 km) at the east and west ends and narrowest (~50 m) on the south, with depths ranging from 1 to 5 m. The central lagoon is ~4 by 1.3 km with depth ranging from 5 to 18 m. Patch reefs of various sizes are located within the lagoon and on the reef sand apron.

This study integrates remote sensing, field, petrographical and granulometrical observations of surficial modern sediments with climate data, oceanographic observations and hydrodynamic modeling. This project focuses on several specific objectives.

- First, the area was mapped using high resolution Quickbird satellite imagery revealed the diversity of carbonate producing biota and geomorphic elements found on

Palau Layang Layang and provided the setting for the spatial context for the field survey (sampling strategy and oceanographic sensor placement).

- Second, during the field survey in July 2017, 190 surficial samples were collected across transects of the atoll (Figure 1B). Detailed field observations of the coral and other carbonate producing biota, bottom types, physical and biological structures, and oceanographic conditions were also recorded. Following the field survey, petrographic and granulometric analyses of the surficial sediments samples characterized the type and quantity of the grain size, sorting, composition, and abundance for the samples (Figure 1C, 1D, and 1E).

- Third, an Acoustic Doppler Current Profiler (ADCP) meter, wave gauges (pressure sensors), light and temperature oceanographic sensors were deployed, recovered after five weeks (approximately one lunar month), and their data recovered and processed. Additionally, a high resolution (~ 2.5 m) bathymetric survey was conducted across the atoll. This information provides the basis to model a range of oceanographic processes on the atoll, and explore origins of geomorphic elements (e.g. reef sand apron) and sediment transport pathways using DHI's M-21 hydrodynamic modeling software. These sedimentology and hydrodynamic modeling results will be integrated within a GIS framework. This analysis will explicitly compare spatial variability in carbonate production, sedimentology, geomorphologic elements, and hydrodynamics to explore potential linkages.

- Finally, no other isolated carbonate platform in the geologic record is exactly like modern Pulau Layang-Layang. Thus, using the insights from the modern as a starting point, the ultimate objective is to explore potential geological variances by numerically modeling a suite of conceptual models with different key input parameters and geomorphologies (e.g. wind direction, waves, monsoon patterns, regional currents, sea level changes and tidal ranges). This step enables the isolation and analyses of the variables to assess their specific and combined influence upon the system across a spectrum of isolated carbonate platform settings.

Deliverables

This study supports the broader multi-year project detailing the influence of oceanographic processes on the sedimentology, geomorphology, biota and sediment transport of isolated carbonate platforms. Specifically, this study details the distribution of biota, sedimentology, climate, and bathymetry of the Holocene isolated carbonate platform in the South China Sea, as well as demonstrates variations of sediment composition and accumulation by geomorphic element. Hydrodynamic modeling results link specific controls (wind, waves, currents, tides and bathymetry) on sediment transport and deposition within the various geomorphic elements in this system. Creating and modeling a series of conceptual models, with different characteristics and parameters than those of the Layang-Layang system, provides insights into the controls on sedimentologic variability for carbonate platform systems in the rock record. This study supports the collective efforts of the larger project generating data and insights for conceptual models for heterogeneity in carbonate platform analogs and examining broader changes and oceanographic controls on variability, with the goal to provide more accurate information to improve conceptual depositional models and heterogeneity in their ancient analogs.

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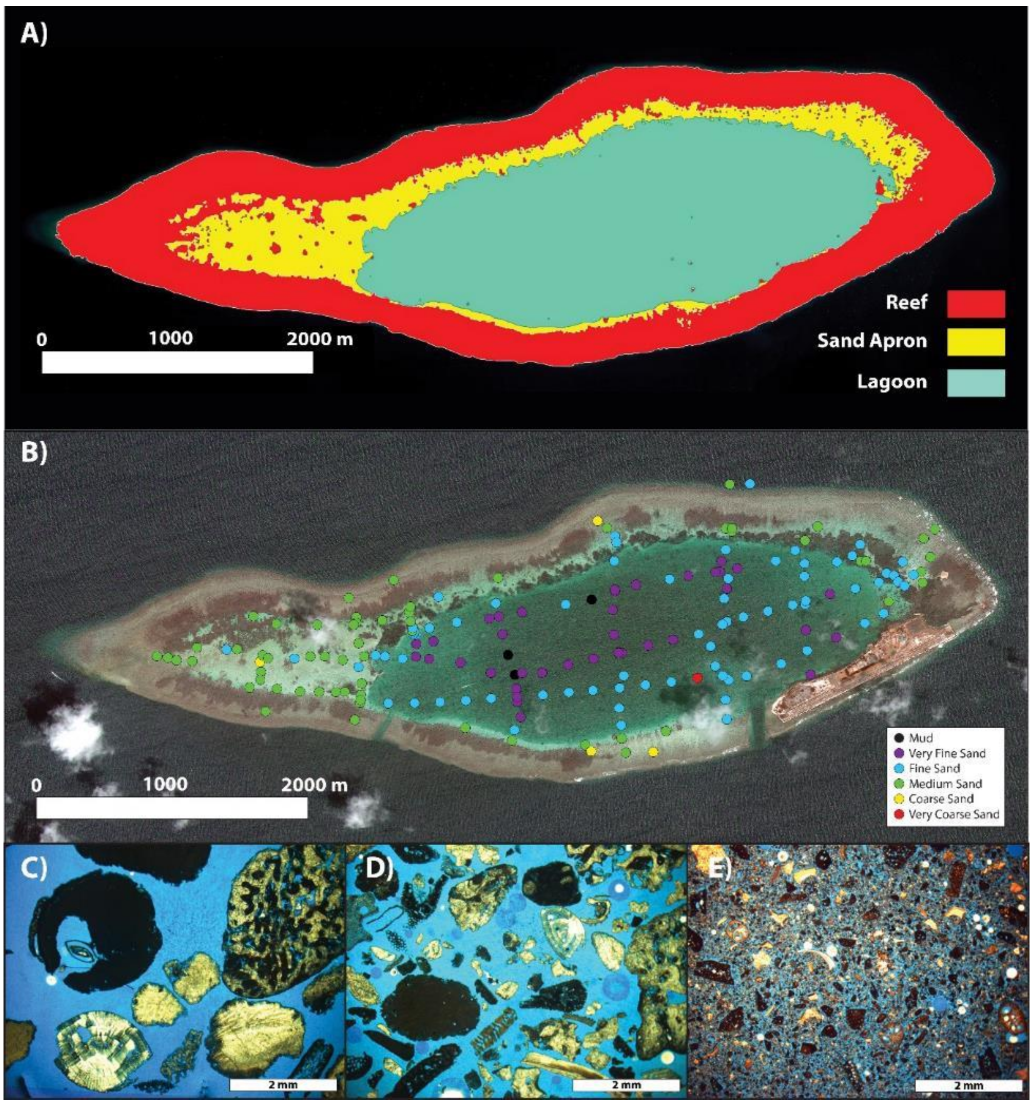

__Figure 1__. Remote sensing and petrographic images of Pulau Layang-Layang. A) Interpreted image showing reef, sand apron, and lagoon geomorphic elements. B) Image showing mean grain size of granular sediment (denoted by colored circles at surficial sample locations). Representative petrographic images from each major geomorphic element C) reef, D) reef sand apron, and E) lagoon.

Integrated Field and Modeling Analysis of Oceanographic Controls on Sedimentology of Holocene Ramp Carbonates: Yucatán Shelf, Mexico

Thomas C. Neal, Gene Rankey, and Christian M. Appendini

SUBSURFACE APPLICATION: Many carbonate reservoirs represent deposition in ramp settings, including the Permian San Andres and Grayburg formations, Permian Basin, Jurassic Hanifa and Arab formations, Middle East, Jurassic - Cretaceous strata of north Atlantic and GOM. This system is a "mixed heterozoan-photozoan" system as well, and can provide insights into Cenozoic Caribbean and Southeast Asia analogs.
STATUS: Part of a long-term project in progress
TIMING: Project will be completed with final report by end of 2019
FUNDING: Full from KICC, GSA, SEPM and AAPG

Purpose

Many ancient carbonates ramp deposits are prolific hydrocarbon reservoirs. Although sequence stratigraphy of such successions is well-documented, the complex processes controlling sedimentologic variability are less well understood (Wright and Burchette, 1998), in part due to the paucity of modern analogs. To develop more rigorous predictive conceptual models for the sedimentation and dynamics of carbonate ramps, this study characterizes the Holocene northeast Yucatán ramp system to enhance understanding sedimentary dynamics of carbonate ramp systems. It specifically tests the hypotheses that ***hydrodynamics and bathymetry directly influence sediment characteristics (size, sorting and type) and geomorphology of carbonate ramps.*** Understanding hydrodynamics and carbonate sedimentology of ramps are important for constructing depositional models of variability within analogous ancient ramps.

Project Description

The study area (Figure 1A,B) lies on the northeastern coast of the Yucatán peninsula. Located in the tropics along the southern Gulf of Mexico, the broad marine ramp dips gently and extends northward out to 245 km from the long (350 km) and low-lying coastline system of beaches, lagoons and barrier islands (Appendini et al., 2012). Siliciclastics are rare in the region and the ramp is covered by sheets of carbonate sand with widely scattered reefs (Logan, 1969). Geomorphic elements within the study area include the Isla de Holbox, a long (30 km) and narrow (1.5 to 3 km) barrier island, with near- and off-shore areas of the gently dipping homoclinal Yucatán ramp to the north, and the Laguna de Yalahau, a large (300 km^2) protected muddy lagoon to the south (Figure 1C).

To explore the hypothesis, this study integrates remote sensing, field, petrographical and granulometrical observations of surficial modern sediments with climate data, oceanographic observations and hydrodynamic modeling. To test the hypothesis, this project focuses on several specific objectives. First, the area was mapped using remote sensing data with Landsat and RapidEye satellite imagery, and a bathymetric survey acquired during field work provides detailed geomorphologic and bathymetric information of the research area, and the spatial context for all sampling and subsequent modeling. Second, nearly 200 surficial sediments samples from nine onshore to offshore transects were collected and the petrographic and granulometric analyses conducted describing the type and quantifying grain size, sorting, composition, and abundance (Figures 2 A – F). Next, the physical oceanographic and metrological conditions are characterized using *in-situ* tide, wave and current measurements and regional data. A variety of regional climate data sources were utilized along with hydrodynamic measurements from two Acoustic Doppler Current Profiler (ADCP) meters (during the mid-February to mid-March 2014 field study period). This information also provides the basis to analyze the effect of a range of oceanographic processes (tide, wave and current) on sediment transport using DHI's M-21 two-dimensional hydrodynamic modeling software. Sedimentology and hydrodynamic modeling results were then integrated within a GIS framework. This analysis will explicitly compare spatial variability in sedimentology, geomorphologic elements, and hydrodynamics to explore potential linkages.

It is probable that no other ramp in the geologic record was exactly like the modern Yucatán. Therefore, using the insights from the modern as a starting point, the final objective is to explore potential geological variances by numerically modeling a suite of conceptual models with different geomorphologies and key input parameters (e.g. wind direction, waves, regional currents and tidal ranges). This step enables the isolation and analyses of the variables to assess their specific and combined influence upon the system across a spectrum of ramp settings.

Deliverables

This study supports the broader multi-year project re-examining a classic ramp system that has not been systematically explored in more than 40 years. Specifically, this study details the sedimentology, climate, and bathymetry of the Holocene ramp system of northeastern Yucatán, as well as demonstrates variations of sediment composition and accumulation by geomorphic element. Hydrodynamic modeling results link specific controls (wind, waves, currents, tides and bathymetry) on sediment transport and deposition within the various geomorphic elements in this system. Creating and modeling a series of conceptual models, with different characteristics and parameters than those of the Yucatán ramp system, provides insights into the controls on sedimentologic variability for a greater number of ramp systems, including those in the rock record. This study supports the collective efforts of the larger project generating data and insights for conceptual models for heterogeneity in ramp analogs and examining broader changes and oceanographic controls on across- and along-strike variability. Understanding the variability in sedimentologic and the hydrodynamic conditions and their controls upon carbonate ramps successions can provide more accurate information to improve depositional models within these systems and their ancient analogs.

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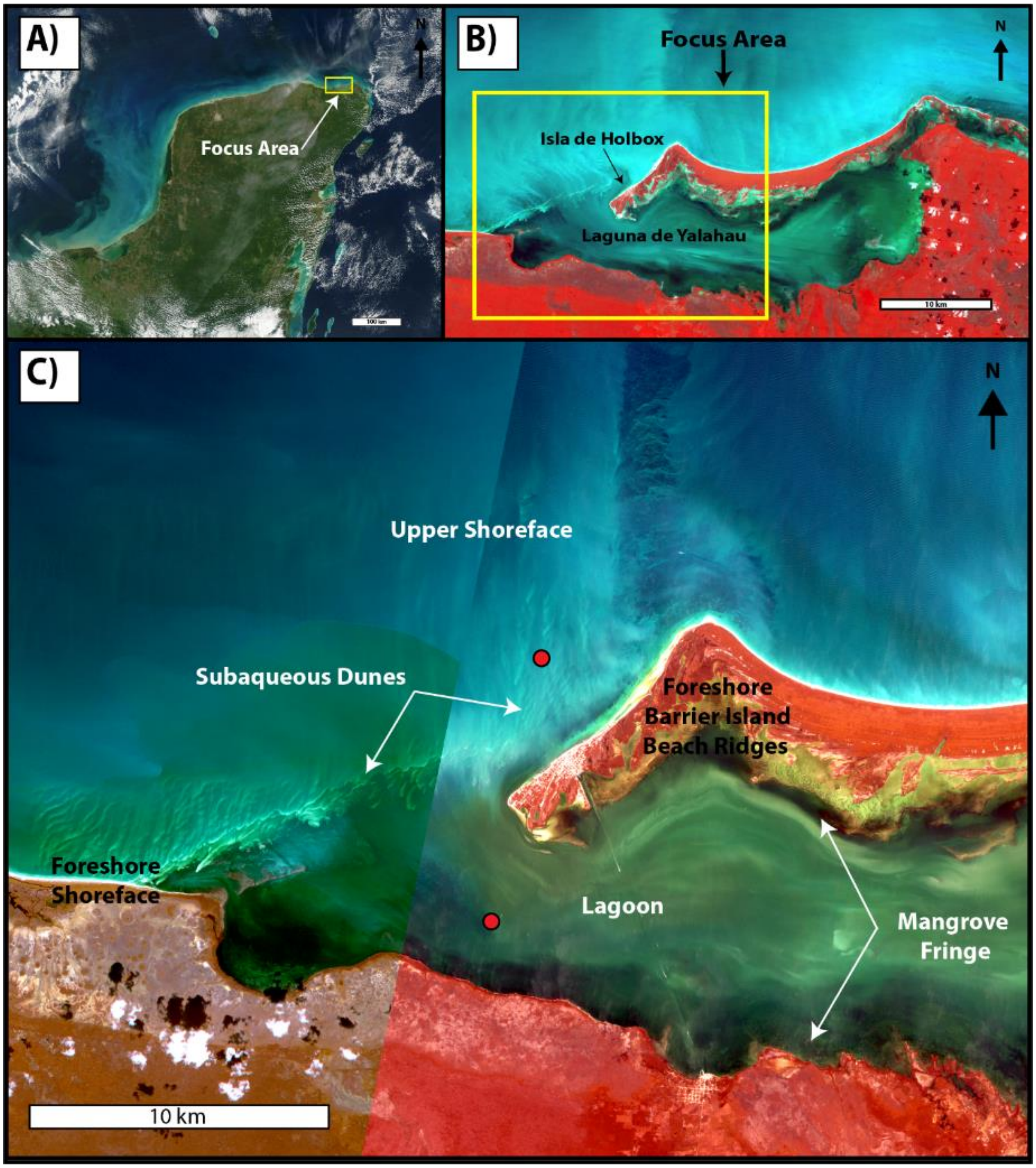

Figure 1. *Remote-sensing images of the Yucatán Peninsula, Yucatán Shelf, and nearshore geomorphology. A) Location of study area offshore of the northeastern Yucatán peninsula note shallow turbid nearshore water of broad shallow Yucatán Shelf. B) Remote sensing image with location of the Isla de Holbox focus area and highlighted in the yellow box. C) Focus area showing geomorphic elements including upper shoreface, subaqueous dunes, foreshore barrier island with beach ridges, and the lagoon with mangrove fringe. Red circles indicate deployment locations of in situ current meters.*

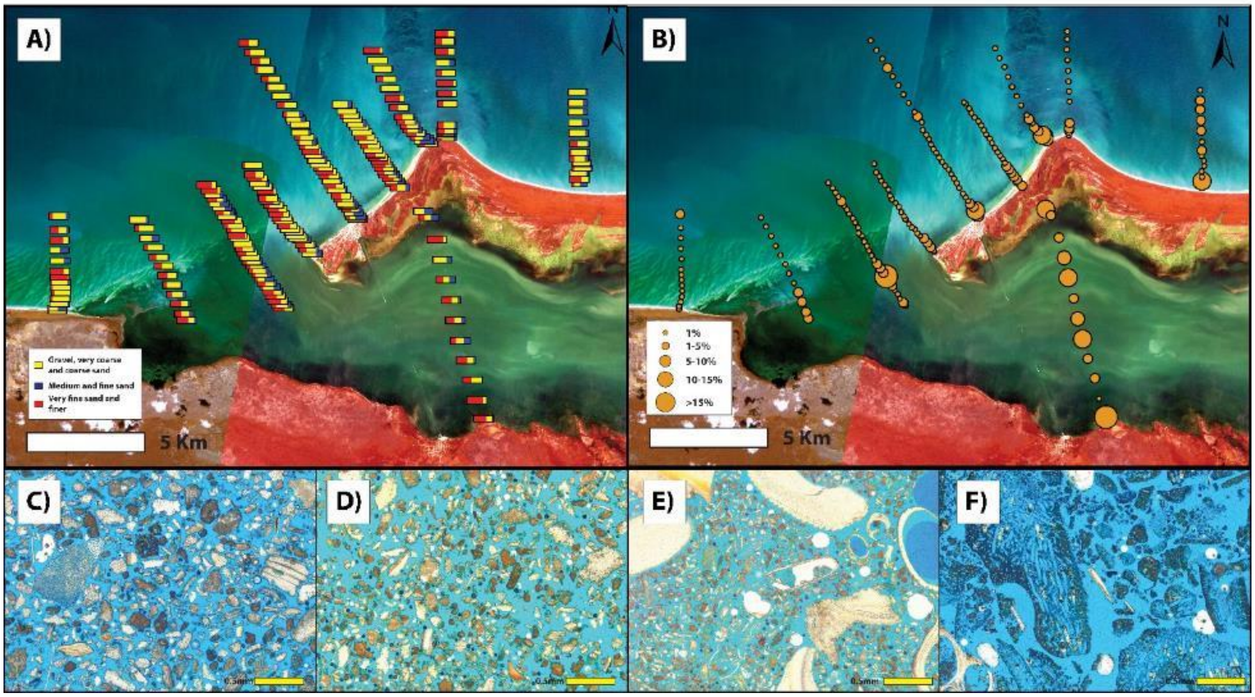

Figure 2. *Sedimentologic trends and petrographic images. A) Grain size distribution and B) mud percentage along surficial sample transects. Representative petrographic images from each major geomorphic element C) upper shoreface, D) subaqueous dunes, E) foreshore/shoreface, and F) lagoon.*

Redox-Sensitive Chemical Elements of Upwelling Ramp Systems: A Comparative Study of Modern and Ancient Carbonates

Gene Rankey, Rodrigo Garza-Perez, Hassan Eltom, Steve Hasiotis

SUBSURFACE APPLICATION: Upwelling can impact facies (e.g., occurrence of heterozoan association), facies successions (e.g., platform drowning), early diagenesis, and organic matter abundance and type in carbonate systems.
STATUS: Ancient aspects and modern project nearing completion
TIMING: Field work completed in mid-2018; results reported spring 2019 KICC meeting
FUNDING: Funded by Petroleum Research Fund, partial funding by KICC

Objective and Relevance to Sponsors

Heterozoan carbonate and biosiliceous facies can contain large hydrocarbon reserves (Rogers and Longman 2001; Gates et al. 2004), including Lower Carboniferous biosiliceous accumulations in North America (Mazzullo et al. 2009). In the modern, heterozoan and biosiliceous facies are common in temperate or cold climate settings, but these types of deposits also can be found in tropical and subtropical shelves, with upwelling playing a primary role in creating conditions favorable for these associations (e.g., Gammon et al. 2000; Gammon and James 2001; Westphal et al., 2010). Although the influences of water temperature and nutrients can be clear in modern heterozoan and biosiliceous sediment, the processes responsible for the deposition of these facies in ancient carbonate ramp successions can be less evident based on physical or biological sedimentary structures or faunal composition alone (Klicpera et al. 2015). To provide an additional arrow in the quiver of interpretive tools for understanding the origin and dynamics of carbonate systems, this project tests the hypothesis that ***carbonate (heterozoan) and biosiliceous sediments in areas impacted by upwelled waters (at least seasonally dysoxic to anoxic settings) are enriched in redox sensitive elements.*** The value of such a study lies in assessing geochemical proxies for oceanic productivity variations that impact (and thus could be used to predict) carbonate, biosiliceous, and organic-rich deposits.

Background and Methods

Recent efforts (Lowery and Rankey, 2017; Tom Neal's thesis, in prep.) revealed the occurrence of nearshore (upper shoreface to lagoon) organic-rich deposits (some in excess of 10% TOC), and heterozoan carbonate (mollusks, forams, barnacles - corals, ooids, and peloids are absent) and biosiliceous (diatoms and sponge spicules) sediment. A previous study (Lowery and Rankey, 2017) suggested that upwelled waters moving near the shoreline westward across the Yucatan Shelf include nutrient-rich, cool water that in turn promotes the heterozoan and biosiliceous sediment.

The objectives of this study are to compare geochemical signals (redox sensitive elemental composition) of heterozoan and biosiliceous sediments in modern (Yucatan) and ancient (Jurassic Hanifa Formation, Saudi Arabia) ramps to help to assess the role of upwelling on their sedimentation. For this purpose, this study will investigate modern ramp sediments (Yucatan Peninsula), and relate those data to water-chemistry data to develop a conceptual model. The results will be compared to sedimentological, geochemical, and ichnological character of ancient strata of an ancient ramp system (the Hanifa Formation, Jurassic, Saudi Arabia) to explicitly test the model.

To test the hypothesis, this project includes several specific objectives on the Holocene ramp system (Yucatan shelf):

- *Characterize oxygen, salinity, temperature, and pH across areas impacted by upwelled waters*. Recently collected data from winter and summer (2018) deployments revealed episodic (seasonally) cool and nutrient-rich water on this shallow shelf.

On the modern ramp system Yucatan Peninsula and the Jurassic Hanifa Formation (central Saudi Arabia, an ancient ramp system):

- *Map elemental composition in sediment from across the range of environments impacted by upwelled waters*. Data should reveal spatial (Yucatan; from lagoon to upper shoreface; also changes along the shelf, with changes in distance from the source) and temporal (Saudi; through the stratigraphy of the Hanifa) changes in trace and rare-earth elements.
- *Screen redox sensitive elements for diagenesis and contamination by detrital materials*. We expect to find minimal contamination by detrital quartz and diagenesis in the modern, but varying levels in the Jurassic; these will be factored out.
- *Compare sediment types and abundances to redox sensitive elements (upwelling indicators*), on first on modern, then on the ancient, system. We expect that relative abundance of different types of carbonate and biosiliceous grains are related to changes in abundance of redox-sensitive elements. For example, we expect to find that sediment enriched in elements suggesting more reducing (nutrient-rich) conditions will contain more abundant biosiliceous material (mostly sponge spicules; also favored by elevated nutrients).

The data from these two areas provide the basis for the following objectives:

- *Generate a first-pass conceptual model*. Comparisons (process-product relations) from the modern ramp provide the basis for a conceptual model for calibration that can be used for interpretation of the Jurassic system.
- *Independently test the relations using ichnology*. Previous study of the Jurassic outcrop focused on characterizing trace fossil type, abundance, and diversity. These ichnologic data provide insights into oxygenation levels, information that can be used to independently test and validate the conceptual model

Deliverables

The results of this project will compare and contrast the elemental composition of heterozoan and biosiliceous facies of modern and ancient ramp systems. Based on a well-constrained modern analog, the data will define distinctive geochemical signals of upwelling, data which will help in constraining the genesis of heterozoan and biosiliceous facies in the rock record. If our hypothesis is correct, the results will demonstrate linkages between elemental composition of heterozoan and biosiliceous facies and redox conditions related to upwelling. These linkages should provide the basis for a conceptual predictive model for the depositional controls on the sedimentation of heterozoan and biosiliceous facies, and the associated organic-rich accumulations.

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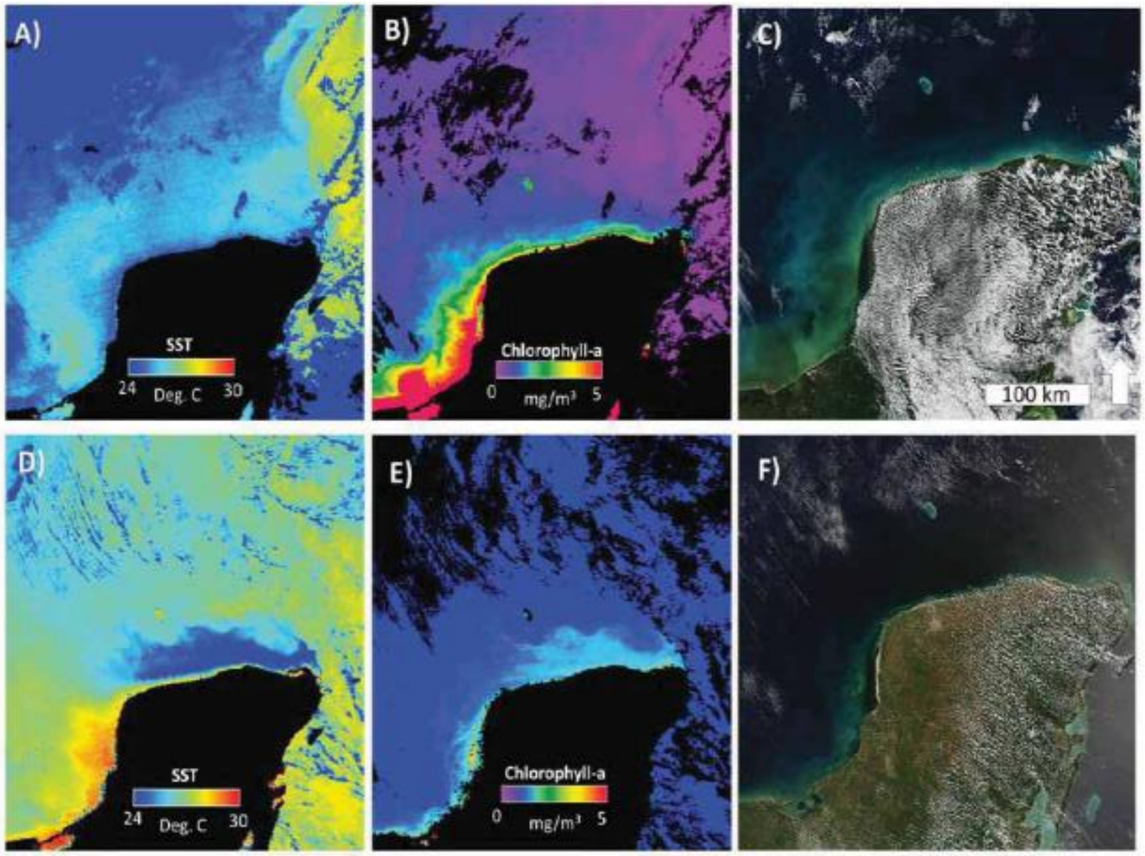

Figure 1. *Upwelling indicators. Coupled sea surface temperature (SST), chlorophyll-a levels (Chl-a), and turbidity illustrating variability off the coast of the Yucatan Peninsula. A-C) Representative winter conditions, January 5, 2014. A) SST showing waters 24-26°C along the Yucatan coast. B) Chl-a levels indicating elevated nutrients along the western Yucatan coast. C) Visible image emphasizing high turbidity along the north and western Yucatan coast, caused by plankton blooms. D-F) Illustrative spring-summer conditions, May 17, 2015. D) SST illustrating cooler (upwelled) waters (≤24°C) off the northern Yucatan coast. E) Chl-a levels along the coast; nutrient levels are elevated (up to 2 mg/m3), but lower than in the winter (Part B). F) Turbidity along the coast of the Yucatan is less during the spring than in the winter. From Lowery and Rankey, 2017.*

Comparative Morphometrics of Facies Patterns of Carbonate Isolated Platforms and Rimmed Shelves: Holocene, Southeast Asia

Gene Rankey, Georg Warrlich, and Erwin Adams

SUBSURFACE APPLICATION: Understanding and predicting facies distribution and sizes in carbonate isolated platforms and shelves, most directly related to Cenozoic systems of Southeast Asia and the Middle East
STATUS: Part of project completed, project expansion proposed
TIMING: Phase 2 results expected in 2020
FUNDING: Seeking funding

Objective and Relevance to Sponsors

Carbonate strata form important reservoirs in Southeast Asia. Many of these systems represent Eocene-Miocene isolated platforms and rimmed shelves, in which reservoir quality is highest in depositional facies associated with coarse, reef-derived sand and gravel. Although seismic data from some of these systems illustrate platformward progradation of reef sand aprons, in most, such direct facies indicators are absent (e.g., Masaferro et al., 2003). In such scenarios, geological analogs can provide conceptual models and as raw data to predict facies dimensions, orientation, and configuration. Modern Southeast Asia carbonate systems have been interpreted to be grossly analogous to the region's Cenozoic systems (e.g., Wilson, 2011), but the Holocene carbonates of this area have not been examined systematically. To fill this gap, the overall objectives of this study are to ***systematically examine and quantify spatial facies patterns of Holocene southeast Asian isolated platforms and rimmed shelves***, ***and relate these patterns to controlling processes***. Rankey (2016) presented final results from 27 isolated platforms of the South China Sea, and this effort proposes a project that aims to expand on those insights by including 1) more geographic diversity and 2) rimmed shelves.

Background and Methods

Recent efforts (Rankey and Garza-Perez, 2012) focused on mapping spatial patterns of facies on isolated platforms using lower-resolution (25-30 m^2 pixel) Landsat data, and compared the spatial patterns to oceanographic processes. In addition to mapping and quantifying facies patterns at a higher level of detail (<2.5 m^2 pixels), this project built (and will continue to build) on that earlier project in three important ways: A) Mapping more platforms, and at a higher resolution, and expand to rimmed shelves; B) Expanding the range of "process space" to include more southeast Asian examples of more direct relevance to sponsors; and C) Examining the nature and rates of change on platforms. It will provides data that will be linked to the subsurface by construction of seismic models to explore the geophysical expression of different geological scenarios (see Duarte and Rankey proposal).

Phase One of this project included analysis of a suite of multi-temporal remote sensing images from 25+ isolated platforms in South China Sea (Spratly and Paracel islands) (Figure 1). Phase Two will expand to include additional platforms and several rimmed shelves. For each area, QuickBird, WorldView or GeoEye 4-band multispectral remote sensing data (<2.5 m^2 pixels) over each platform provide the fundamental data. The data analysis includes:

1) Remote sensing data queried to derive *thematic maps* of spectral lithotopes, interpreted in the context of depositional facies/geomorphic elements. These maps were generated using a mix of unsupervised and supervised classification techniques (e.g., Figure 2A,B).
2) These thematic maps form the basis for the *quantitative analysis of spatial patterns*. Utilizing a GIS, the data were queried and characterized in terms of facies element composition (what is there), size (how big are they) and configuration (how are they spatially arranged), expressed in terms of probabilities (Figure 2C,D).
3) Multi-temporal data from several areas provide the foundation for *analysis of change* on these systems, with focus on reef sand aprons. Data from 2001-2004 (the oldest commercially available high-resolution remote sensing images) and 2012-2019 ("recent") from the same platforms illustrate changes in spatial extent of facies (and human constructs), and simple numerical models quantify the nature and rates of change.

Deliverables

The primary results of the study to date include qualitative and quantitative analyses of facies patterns of South China Sea isolated carbonate platforms. The data are available presently on the KICC sponsors web page. Pending additional support, the project plan is to expand to other southeast Asia analogs, including other isolated platforms and rimmed shelves, of the Celebes, Sulu, and Java seas.

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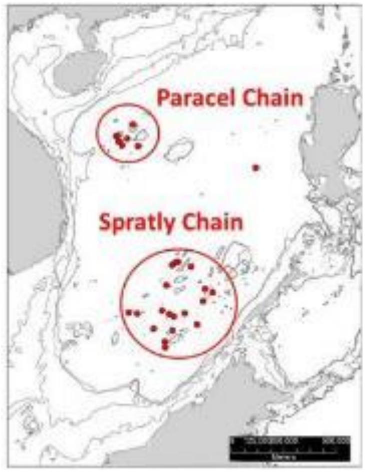

***Figure 1**. Map of general location of data analyzed to date. Data include a suite of platforms, in a range of settings, to attempt to sample the range of oceanographic and tectonic variability. Phase 2 will expand geographically and include rimmed shelves as well.*

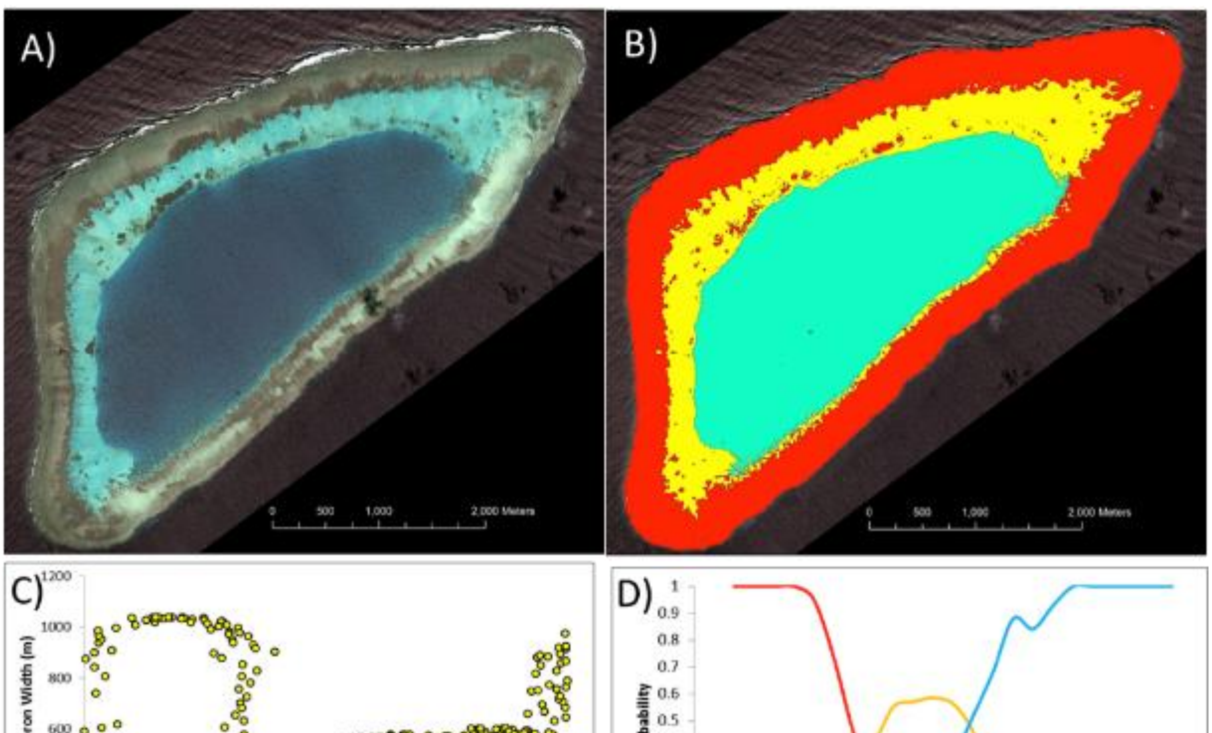

***Figure 2**. Representative facies attribute data from Pigeon Atoll (Spratly Chain). A) Uninterpreted remote sensing image; B) Thematic map of facies; C) Width of reef sand apron vs. orientation of the margin (direction the margin faces); Note the wide aprons of Northwest-facing margin; D) Plot showing the probability of occurrence of a given facies with distance from margin. The colors used correspond to the thematic map of facies in (B).*

Controls on Sedimentation and Diagenesis in Modern Pre-Salt Analogues

Randy Stotler and Jennifer Roberts

SUBSURFACE APPLICATION: Analogs for pre-salt Brazil and offshore Angola
STATUS: Proposed Project
TIMING: Upon Funding
FUNDING: None

Purpose

Saline groundwater-fed interface environments in arid and semi-arid regions are critical zones of lacustrine and palustrine carbonate precipitation. These areas include chotts, sabkha, salars, salt pans, and alkaline or salt lakes. Although climatic conditions clearly play a first order role in the chemical evolution of these environments, the early diagenetic processes are highly variable. and have strong linkages to microbial processes. Reclassification of some lacustrine oil "shales" as carbonates from alkaline lakes, accentuates the importance of gaining insights from modern analogues on the development of these facies (Alonso-Zarza and Wright 2010, Wright 2012). This recent attention has highlighted the variation of microbial build-ups, and the large differences between marine and lacustrine carbonates precluding a "simple comparison" between the two depositional environments (Wright 2012). Mg-silicates, a common precipitate in alkaline lakes, could affect carbonate formation and subsequent preservation, possibly limiting microbial carbonate production (Wright and Barnett, 2014). As a result, it is critical for research to be conducted on facies models related to silicate-carbonate interactions and microbial build-ups (Wright 2012). Our recent research also suggest the source of CO_2 and the cause of the buildup of CO_2 within lake sediments needs further study. *The goal of this study is to investigate the physiochemical controls, including the role of geogenic and atmospheric CO_2 on abiotic and microbially mediated carbonate and silicate formation through a series of laboratory experiments*. Studying these processes will lend insight into the formation of microbialites in saline environments, their morphogenesis and potential tool in biostratigraphic correlation, and diagenesis and reservoir development (including methods for identifying locations of CO_2 buildup), with relevance towards a number of carbonate reservoirs.

Project Description

To develop a depositional model for the pre-salt deposits, it is critical to understand the microbial and geochemical reactions that lead to mineral precipitation and preservation. We are investigating carbonate and Mg-silicate formation and preservation in sediments through a combination of biogeochemical mineralogical and isotopic analysis and experimentation. Briefly, the carbonate and silicate formation environment is explored in column and evaporation experiments, where salinity, water chemistry, initial sediment mineralogy, atmospheric and fluid temperature, surface water algal and microbiological flora, and CO_2 sources and concentrations are varied. Major and trace elements including nutrients, organic carbon and stable isotopes (O, C, Cl, Br) will be monitored throughout the experiments. The corresponding filtrate and sediment (or mat) samples are digested for the same parameters and additionally characterize the mineralogy, morphology, and relationships therein (e.g. Phillips-Lander et al., 2013) using XRD, thin sections, and SEM.

Deliverables

Specific deliverables include: 1.) Improved understanding of the controls on carbonate and silicate deposition and preservation in alkaline hypersaline lakes; 2.) Mechanistic, morphological and kinetic data on *in situ* of carbonate formation with and without reactive surfaces in hypersaline lakes; and 3.) At least one manuscript and development of a larger NSF or industry supported proposal.

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Comparative Ichnology of Holocene and Pleistocene Successions: The Role of Biota in Sediment Reworking

Steve Hasiotis, Gene Rankey, and student

SUBSURFACE APPLICATION: Carbonate reservoir rocks of late Paleozoic to Neogene in age in the oil and gas fields around the world, particularly of Jurassic and Cretaceous ages
STATUS: Phase 1 of this project; expanding on previous work
TIMING: 2 years; data being collected; student thesis research being written up; results being reported as produced, thesis (one manuscript) writing underway
FUNDING: Seeking funding from KICC sponsors; opportunity for additional funding for spinoffs for more research; 2 (MS student)–4 (PhD student) years

Purpose

After deposition, carbonate sediment texture can be modified by the activity of organisms; these processes can either degrade or enhance porosity and permeability. Although descriptions of carbonate successions commonly refer to "burrows" or "bioturbation," systematic descriptions and assessment of their possible effect on reservoir quality are few (Cunningham et al. 2009). ***To start to address this need and to understand the nature, extent, and controls on biomodification in carbonates, this study proposes a comparative analysis of ichnologic patterns between recent and Pleistocene carbonate, shallow shoreface successions, testing two linked hypotheses: 1) Ichnologic patterns (trace fossil type, density, depth) in Holocene and Pleistocene successions vary among environments (beach ridge, foreshore, upper shoreface, lower shoreface); and 2) Ichnologic patterns in each environment are similar in Holocene and Pleistocene examples.***

Project Description

Our preliminary analysis of outcrops exposed on the western margin of Crooked Island and Long Cay (Crooked-Acklins Platform, southern Bahamas) revealed a Pleistocene reef, shoreface, and backshore succession. Grainstone bodies, the focus of this research, form well-defined shore-parallel ridges in plan view. These deposits include shallowing-upward successions, from upper shoreface to back-beach deposits with ubiquitous physical sedimentary structures, at scales from lateral accretion surfaces several m tall to trough cross-stratification to current and wave ripples. Akin to siliciclastic analogs, trace fossil diversity and abundance varies with the interplay of depositional energy, sedimentation rate, oxygenation, and salinity. Trace fossils in this carbonate succession can appear at a range of density, from isolated, individual traces to complete reworking of the stratal bedding and texture (Figure 1).

Pleistocene stratigraphy of Crooked Island and Long Cay are being described by measuring standard stratigraphic sections. We expect to describe 5-7 sections and encounter environments from reef, shoreface, to back-beach; sections will include descriptions of grain size, type, sorting, and physical sedimentary structures. We will characterize vertical and lateral changes in trace fossil associations as well. From these data, we will be able to place the trace fossils into the depositional framework. We will systematically collect ~50 samples for slab, thin section, CT-scan, and phi/k analysis.

To characterize the Holocene shoreline system, three transects will run normal to the shoreline offshore, but sampling density and design will focus on capturing the range of water depths and geomorphic variability. The subaqueous portion of each transect will be studied via SCUBA. At each location, the general sedimentologic and ecologic aspe cts of the seafloor will be described (for example, abundance of sea life, presence and distribution of burrowing organisms, physical sedimentary structures such as ripples). In the field, in situ observations will describe the type and size of traces. Across transects, as logistically possible given water depth and energy conditions, a representative suite of burrows will be cast in resin and/or in dental plaster to capture the architectural morphology and determine how it may produce macrochannels and macropores that are (or could) be later filled with different carbonate sediment types (and, potentially modified by diagenesis). Upon return from the field, burrow casts will be studied for their morphology and tortuosity in order to understand the number and depth of branching and, by proxy, the form and shape of macrochannels. Sediment samples collected from bioturbated intervals and areas vs. nonbioturbated intervals will be analyzed for differences in grain-size distribution, size, and sorting and facies relations. Sediment from burrow fills will be compared to the surrounding matrix to determine how burrow fills affect local porosity and permeability. All of these data on bioturbation patterns—field and lab analyses—will be tied to the sedimentary and geomorphic remote sensing images to build ichnocoenoses (trace communities) and ichnofacies models and define the relationship between grain size, facies, biogenically mediated porosity and permeability trends. Through this systematic analysis, we expect to find marked differences in grain size, sorting and type, and sedimentary structures and ichnology, both along and across depositional strike.

Deliverables

Although underappreciated in carbonates, trace fossils are important as they provide: 1) important clues to interpreting EODs, as well as syndepositional and postdepositional conditions; 2) information on how bioreworking impacts and modifies the original depositional fabric and texture; 3) biomodified textures commonly have different porosity and permeability than the primary depositional matrix. This phase 1 of this research will provide 1) a catalog of trace fossils, from Pleistocene and Holocene examples, 2) document the environments in which each occurs. These insights, and the assessment of the role of biota in sediment retexturing, will provide new conceptual models for the extent and significance of ichnology in the modification of depositional porosity with respect to geomorphic bodies.

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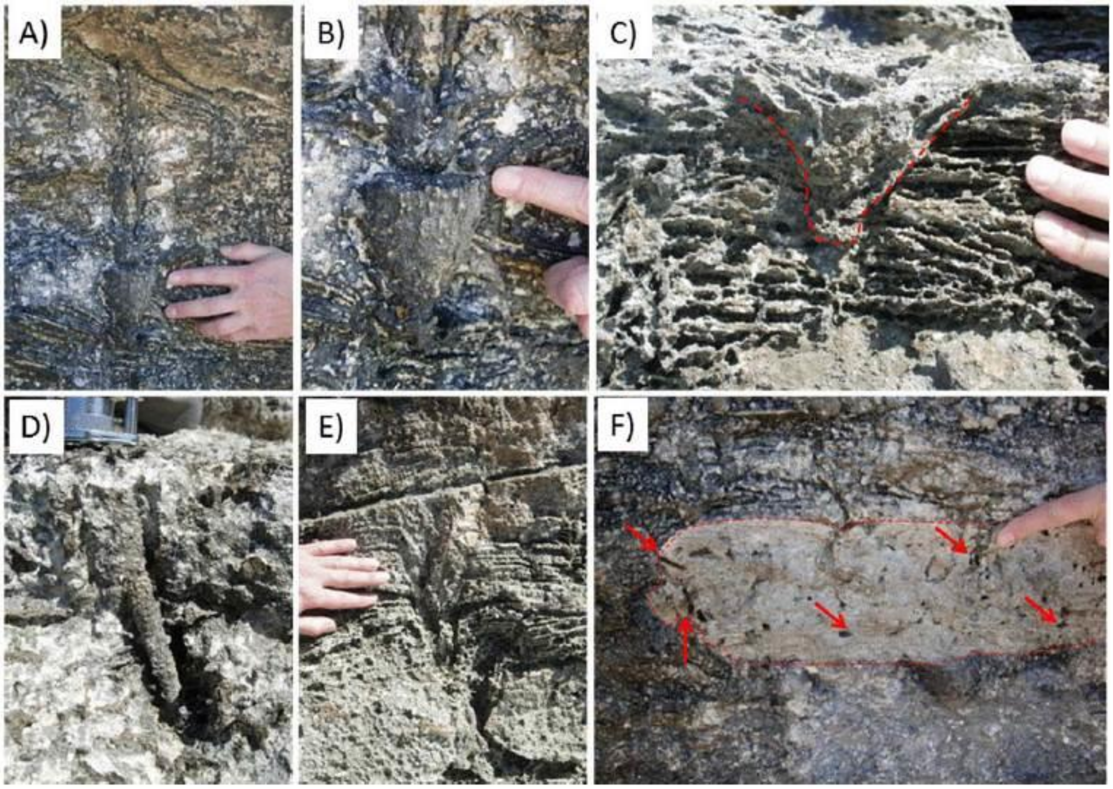

Figure 1*. Shallow marine trace fossils. A–B) Rosselia changing form to* Cylindrichnus*, indicating a change from a cohesive to shifting seafloor sediment. C)* Conichnus*, a resting trace of a sea anemone. D) Vertical* Ophiomorpha*, indicative of higher energy systems in which 1-2 m deep shafts dominate the upper parts of the burrow systems. E) Upper part of* Cylindrichnus*, indicating slower aggradation of the seafloor. F)* Gastrochaenolites, Trypanites, *and* Entobia *visible in cross section of early cemented carbonate seafloor ripped up and redeposited; note borings are found on all of the margins, indicating reworking of the clast.*

Developing Modern Analog Models for Shallow-water Tropical Carbonate Systems in the Rock Record that Developed Under Adverse Photic Zone Conditions, Puerto Rico

Evan K. Franseen, Wilson R. Ramírez Martínez, Students

SUBSURFACE APPLICATION: The various modern heterozoan and photozoan carbonate systems developed around Puerto Rico are analogs for Cenozoic tropical carbonate reservoir systems in the Caribbean (such as the Perla giant gas field, offshore Venezuela) and Indo-Pacific. Lessons from the modern of Puerto Rico can be applied to similar reservoir systems throughout the rock record.
STATUS: Proposed project
TIMING: Long-term research project; initial project 2 years
FUNDING: Seeking funding

Purpose

Current carbonate models applied to the rock record are heavily influenced by studies of modern tropical systems, such as the Bahamas, which consist mostly of photozoan reef systems that develop in clear, warm water photic zone conditions. These models have biased interpretations of tropical carbonate systems in the rock record.

Heterozoan carbonate systems are increasingly being recognized as important petroleum reservoirs in the rock record. Although research on heterozoan systems has accelerated over the last two decades, we still lack understanding of controls on facies types and distribution, stratigraphic architecture, and reservoir character. The understanding of heterozoan systems in low-latitude tropical regions is especially lacking. They are increasingly being recognized in areas that are affected by excess nutrients, and turbid water. In addition, some of these systems can contain abundant photozoans that are able to tolerate higher nutrients, more turbidity and reduced temperatures (herein termed limited photozoan association). ***To better understand these types of atypical shallow-water tropical carbonate systems developed in the ancient, it is important to study modern analogs to develop models. Puerto Rico is chosen for study because it shows variable development of photozoan and heterozoan biota in shallow-water photic zone environments around the island as a result of natural and human-induced variations in nutrients, turbidity, water chemistry, energy and water temperature.***

Project Description

Puerto Rico is ideal for study and development of models because abundant data on sediment and biotic components in shallow-water areas have been already collected around the island (e.g. Figures 1, 2), and expertise and resources are available at the University of Puerto-Rico for further analyses of the data, and for further, targeted study and data collection (e.g. Scanlon et al., 1998; Morelock, et al., 1994; Kågesten, et al., 2015).

An initial phase of study is targeted at assimilating and mapping the data already collected on the different types of heterozoan and photozoan biotic and non-biotic components and sediment in the shallow-water photic zone environments (0 to ~30-50 m depth), and to also relate those distributions to areas of land runoff (both natural and man-made), and oceanographic conditions for which data are available (e.g. water temperature, energy, currents, water chemistry). Those data will be used to identify areas for more targeted studies to further document, sample, and map out distributions of heterozoan and photozoan biotic and non-biotic constituents and sediments and to determine the controls on development. To this extent, samples will also be collected to determine organic content, turbidity, and water chemistry; data on geomorphology, water depth, energy, currents, and water temperature will be integrated.

Overall goals of the study are to provide better understanding of the conditions affecting the coastal areas around Puerto Rico, and specifically map out and link differing carbonate system development (photozoan, heterozoan, or combination of both) around the island with the major factors responsible for the variability to develop predictive models that can be applied to the rock record. Some of the Cenozoic carbonate rock systems preserved in Puerto Rico, and regionally around the Caribbean, are tropical shallow-water systems that developed under adverse photic zone conditions (high nutrients, turbid waters), which prevented the development of typical photozoan-dominated reefal systems and instead were dominated by heterozoans and photozoans tolerant of adverse photic zone conditions (limited photozoan association). A better understanding of the modern system in Puerto Rico and the controls on distribution of carbonate facies could better aid in understanding the similar Cenozoic carbonate systems, some of which form important petroleum reservoirs in the Caribbean (e.g. Perla, offshore Venuzuela) and the Indo-Pacific.

Deliverables

Specific deliverables for the project include maps, cross sections, and data bases on sediment and biotic component distribution, water depths, geomorphology, spatial relationship to areas of land runoff, organic content, and water conditions (energy, chemistry, temperature, turbidity). Overall, the results of this study will provide data on the controls on deposition and distribution of heterozoan and photozoan facies and predictive models that can be applied to systems in the rock record, including those that form petroleum reservoirs.

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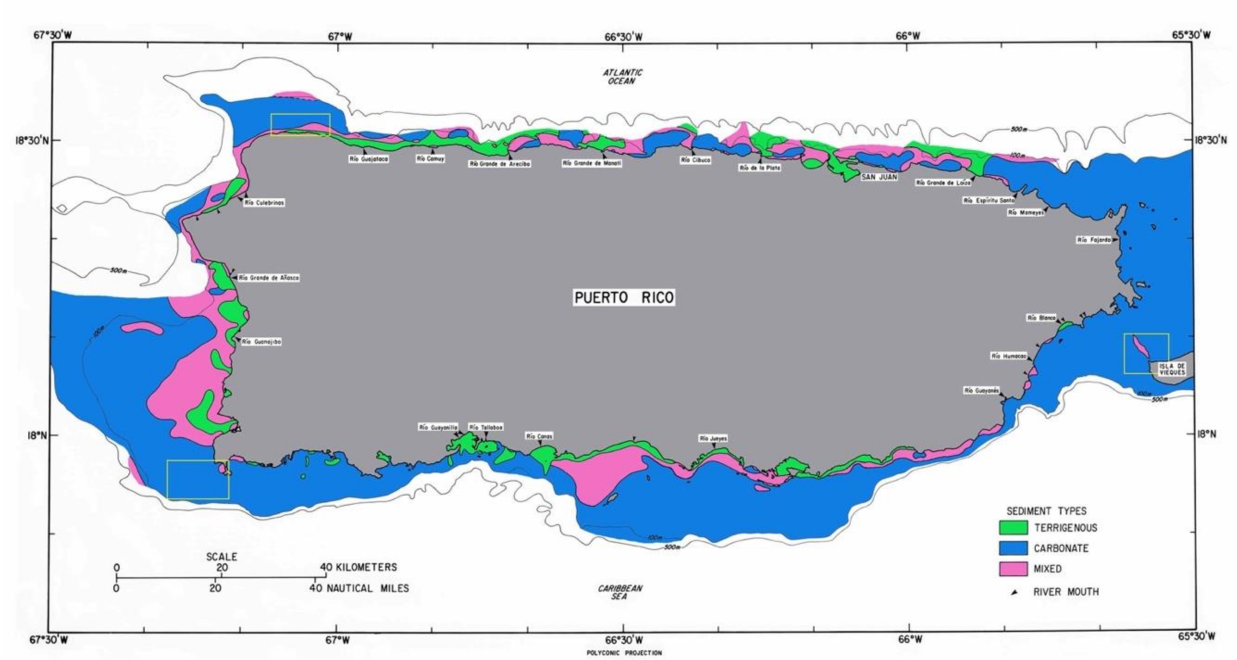

Figure 1. *Map of Puerto Rico showing distribution of differing sediment types around the island and locations of river mouths. From Scanlon et al. (2004).*

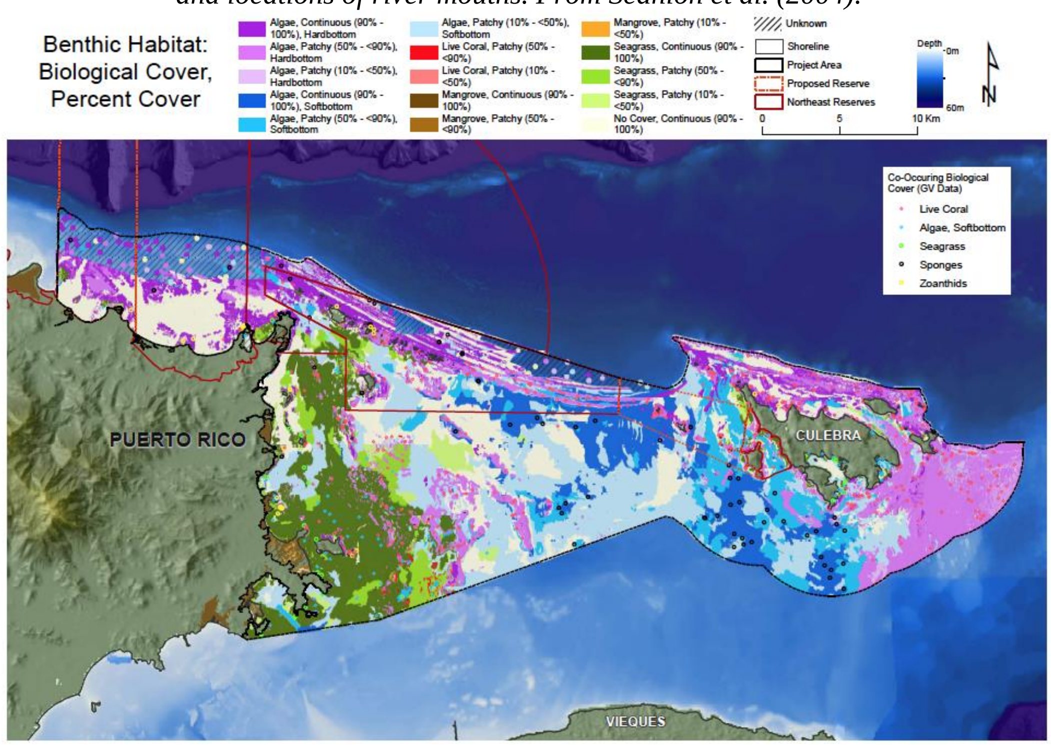

Figure 2. *Map showing benthic habitat, biologic cover, and percent cover on northeastern portion of Puerto Rico to the Island of Culebra. From* Kagesten et al. (2015).

Reservoir Characterization, Petrophysics, and Modeling

Sponsors of the KICC produce hydrocarbons from subsurface reservoirs, commonly utilizing reservoir models. To better understand how models can and do represent the subsurface, and to train students for future endeavors, numerous projects explore subsurface systems using these tools. Examples of some current and pending projects include:

An Integrated Approach for Closed-Loop Microporosity Characterization

PIs: Dr. Masoud Kalantari, Dr. Arsalan Zolfaghari, and Dr. Shahin Negahban
Co-PI: Dr. Franciszek Hasiuk
Co-PI: Dr. Robert Goldstein
Two prospective graduate research assistants

SUBSURFACE APPLICATION: Carbonate and siliciclastic rocks, especially considering the case of low-resistivity pay
STATUS: Long-term project in progress
TIMING: Preliminary results are available now- Upon funding significant results to be reported.
FUNDING: Seeking funding at this point.

Purpose

Petrophysical modeling of multi-phase flow properties strongly depends on accurate characterization of the pore space in reservoirs. Among different geologic formations of interest to the oil and gas industry, carbonates often present a challenge because of their wide pore size distributions (PSD) and variations in connectivity. For homogenous rock samples, pore space can be accurately described using one set of images at a single resolution. For heterogeneous rock samples, however, workflows need to be modified to capture the existence of wide PSD. Therefore, classical methods employed in Digital Rock Physics often fail to provide a valid description of the pore space by overlooking a large number of micropores, which usually account for a significant portion of the pore space in carbonates but are below the resolution of typical imaging methods. This project develops an alternative integrated approach more applicable to wide PSD, and including microporosity.

Project Description

In this project, we employ and further develop a workflow for closed loop microporosity characterization in carbonates and siliciclastic rocks. In the workflow, microporosity is characterized through petrographic analysis of carbonate thin sections and FIB-SEM images. Different types of microcrystals that host microporosity are identified based on crystallometry, morphology, texture, and depositional setting and their origins. PSDs based on sample micro-texture will be used to develop a Dual Pore-Scale Network Model. A macropore network will be generated based on a 3D micro-CT images of the pore space under dry conditions at a single resolution. Micro-pore networks will then be populated to represent microporous areas honoring their spatial locations observed in micro-CT and petrographic images. Rock properties (such as porosity and PSD of micropores) will be used in this process to populate statistically representative micro-pore networks. Having three parameters for characterizing microporous regions (i.e., spatial locations, porosity, and PSD), an algorithm will establish cross-scale connectivity between the two networks by connecting the macro- and micro-pores in close proximity. Geometrical constraints will be considered for populating micro-pores and their connecting micro-throats in 3D. In the micro-CT lab, tagged water will be injected to illuminate the connected pore space and its contribution to effective porosity. This will help to improve understanding of micro-pore connectivities and their effective porosity contributions. This knowledge will then be used to tune our proposed model for constructing representative pore networks for a specific sample of interest. The generated networks are then read by our novel “in-house” **C**arbonate **M**icro and M**A**cro **P**ore-Scale **S**imulator (CMAPS) to simulate a wide range of multiphase flow processes including any sequence of oil, water, and gas injections. The model is capable of simulating fluid/fluid displacements at pore levels in *mixed-wet* systems by handling a wide range of pore-fluid occupancies including *corner* and *layer* flow mechanisms. It calculates thermodynamically consistent threshold capillary pressures for all relevant pore-level displacements including wetting and spreading oil layer formation and collapse. This will improve the predictive capability of the model at low oil saturation. Simulating displacement sequences at the pore level, the model computes capillary pressure, relative permeability, and resistivity index curves for any desired drainage and imbibition flow cycles.

Preliminary Findings

We are already far along on this application. An improved Pore-Scale Network Model is presented in the works by Zolfaghari (2014), and Zolfaghari and Piri (2017), by accommodating microporosity and incorporating calculation of electrical properties. The reservoir carbonate sample used has significant microporosity and the effect of different local porosities and pore size distributions in the microporosity zones was investigated through generating stochastic pore-networks within the Euclidean space occupied by microporosity clusters.

The findings demonstrated non-Archie behavior of Resistivity Index at low water saturation in heterogeneous samples (S-networks and Estaillades limestone) and showed the impact on reserves estimation. Results indicate that pore size distribution (PSD) of micropores of the given sample has a much stronger impact on capillary pressure, relative permeabilities and resistivity index curve, rather than local porosity; porosity comes into play as the micropore sizes increase. Increasing pore sizes for the same porosity resulted in poorer connectivity and hence, poorer electrical conductance. Among all, the pore-networks generated with the chosen small PSD for micropores showed a better match with lab measurements by replicating the heterogeneity of the sample. The Resistivity Index curve for small PSDs showed non-Archie behavior with two slopes that were consistent with the result generated for the heterogeneous Estaillades limestone sample using the same numerical model. It was determined that reserves can be underestimated by 6%, up to 14% (for oil saturation=80-90%) if the Archie equation is used for this specific sample.

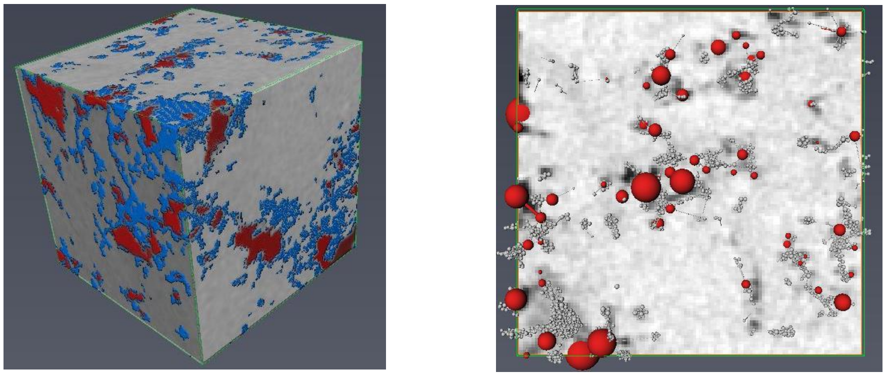

Figure 1. *Segmented sample: blue and red color represents microporosity and macropore space, respectively (left). The final network consisting of macropores (red spheres) and stochastically generated micropores (grey spheres) (right)*

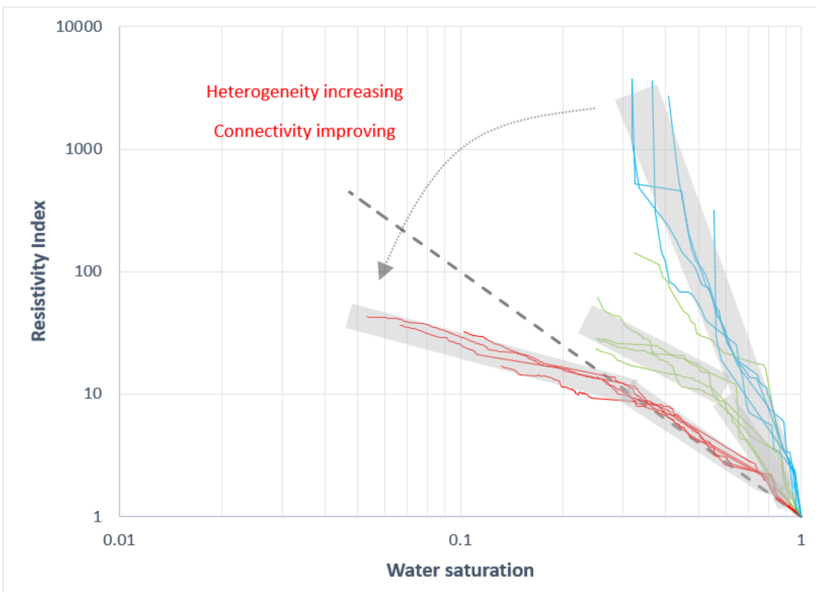

Figure 2. *Resistivity Index curves during primary drainage generated for the all presented pore-networks. Red curves represent S-networks (small-sized micropores), blue — M-networks (medium-sized micropores) and green — L-networks (large-sized micropores). The dashed line represents RI curve calculated using the Archie equation with the saturation exponent of 2.0. Transparent grey areas are shown in order to group the results in one cluster.*

Deliverables

Deliverables to be provided by this project would be interpreted images at different scales (FIB-SEM, Thin section, Micro CT), quantitative pore network models, report and presentation. CMAPS licensing options are available to be discussed.

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Improved pore space analysis for carbonate reservoir rocks using multi-geophysical tools

Chi Zhang

SUBSURFACE APPLICATION: Improved pore space analysis for carbonate reservoir rocks using multiple geophysical characterization tools
STATUS: *Proposed project*
TIMING: *Upon funding*
FUNDING: *None*

Purpose
In accordance with further needs for recovery and utilization of carbonate reservoirs, reliable characterization of pore structure (such as porosity, surface-to-pore volume ratio, pore shape, and pore size distribution) in carbonate rocks is critical. Carbonate rocks have a diverse variety of pore types and very often bi- or trimodal pore size distribution. Previous studies have used a variety of conventional techniques to qualitatively and quantitatively characterize the pore structure of complex geological materials, such as imaging techniques (electron microscopy and X-ray computed tomography) and fluid intrusion (MICP and gas adsorption). However, these techniques are only laboratory based and are costly and limited to narrow detection range. In response to this problem, this project will use two geophysical methods - complex conductivity and NMR, which are shown highly sensitive to pore attributes in unconsolidated samples and sandstone at both laboratory and field scales. This project focuses on developing new algorithm to interpret NMR and SIP signals to better characterize pore structure and determine pore size distribution in carbonate rocks.

Project Description
In NMR porosimetry, efficient distribution of pore size can be estimated from transverse relaxation time (T_2) distribution. Similarly, time constant (τ) distribution derived from measured SIP spectra is attributed to the polarization of electrical double layer (EDL) formed at rock-fluid interfaces (Revil 2012). However, NMR and SIP porosimetry are usually processed and interpreted separately, both require prior knowledge of petrophysical parameters which are either inaccurate or lacking in carbonate rocks (Niu and Zhang 2018). Here we propose a new inversion scheme to joint invert NMR and SIP to extract accurate pore size distribution information from carbonate rocks.

NMR and SIP porosimetry basic
In fast-diffusion regime, NMR relaxation mainly arises from the surface relaxation (Strange et al. 1993) without interference from connected pores (Grunewald and Knight 2009) is considered. Therefore, $\frac{1}{T_2} \approx \frac{a\rho_2}{r}$, where r is pore size, a describes the shape of the pore (a = 3 for spheres), ρ_2 is the surface relaxavity. Pore size distribution thus, could be estimated from T_2 distribution with an assumption of the geometry of the particles. SIP measures the frequency-dependent complex conductivity of porous media at low frequencies. It is sensitive to geometries of the pores which is usually interpreted with EDL

polarization theory which links the radius of EDL curvature with pore size by $\tau = \frac{{r_c}^2}{2D^+}$, where D^+ is the diffusion coefficient of ions in EDL. Based on the petrophysical relationships derived from NMR and SIP porosimetries, pore size itself can be calculated from NMR porosimetry and SIP porosimetry. The inherent links between NMR and SIP principles inspired us to jointly interpret both data to mitigate ill-posed geophysical solutions, for instance, pore size distribution.

Joint inversion process

Both T_2 and τ are linked with pore size, thus the relative amplitudes or intensities $\boldsymbol{f_i}$ act as function of T_2 and τ respectively (Niu and Zhang 2018). By simultaneously proccecing NMR and SIP data, a best estimation of density function for $\boldsymbol{f_i}$ can be inverted based on the input. The output of joint inversion is a spectrum of intensities $\boldsymbol{f_i}$ versus pore size r. A Tikhonov regularization scheme is used to accomplish the inversion by solving the damped least squares problem which minimizing the objective function

$$J_m = \sum_{i=1} \sum_{j=1} \omega_i^d \|d - G(m_k)\|_2^2 + \boldsymbol{\lambda} \omega_i^m \|L(m_k)\|_{1,2}^2$$

where L are the roughening matrices that constrain the smoothness of the pore size distribution, and ω^d and ω^m are weighting matrices. The tradeoff between two data sets is thus balanced by weighting parameter $\boldsymbol{\beta}$. The tradeoff between data misfit and model norm yield the solution controlled by regularization parameters $\boldsymbol{\lambda}$. The inversion problem is solved iteratively using the Levenberg–Marquardt algorithm and the related Jacobian matrix at each iteration is determined analytically by updating parameters. Figure 1 shows the scheme of joint inversion adapted in our work, which includes parameters and each step of both forward and inversion models. Such workflow demonstrated a significant improvement of pore size distribution in sandstone samples. However, our preliminary study shows that the current SIP polarization model fails to capture the complex carbonate polarization behavior therefore yields a poor estimation of pore size distribution in real carbonate samples. We propose to modify the forward model in joint inversion to fully consider variable polarization behavior in carbonate samples. Furthermore, the regularization strategies shall be tested during inversion. The choice of using whether the first order or second order Tikhonov regularization terms needs to be evaluated since it changes the inversion results as smoothing operators of pore size distribution.

Deliverables

This proposed work will facilitate pore space analysis for carbonate reservoir rocks with focus on improved estimation of pore size distribution in real carbonate rocks using field available dataset (i.e., NMR and electrical resistivity data logging data). The proposed approach represents the first attempt to characterize the pore structure of carbonate rocks with varying using these two methods synergistically. Tremendous advantages of such approach can be explored in this study to assess the fluid-flow pathways, and eventually to assist the economic production of hydrocarbons.

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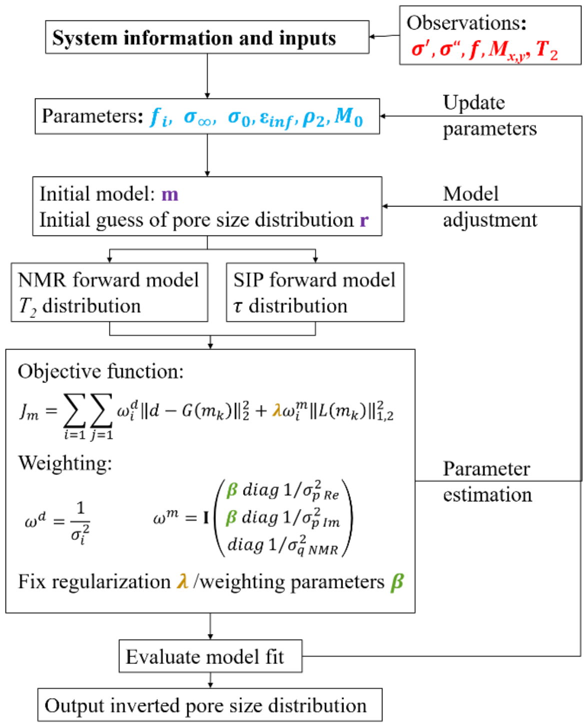

Figure 1. *Workflow of jointly inversing pore size distribution from NMR and complex conductivity data. Red parameters are observables that used as input; blue parameters are model fitting parameters; purple letters are initial guess of model; yellow and green letters are inversion controllers.*

3D Printing Pore Space: Effect of Pore Network Magnification and Material on Permeability

Franek Hasiuk (Kansas Geological Survey)

SUBSURFACE APPLICATION: Basic research into factors governing pore-scale fluid flow (pore network geometry/connectivity and physics of surfaces)
STATUS: Long-term project in progress
TIMING: Upon funding
FUNDING: Awaiting funding

Purpose

- To develop a scaling law that describes how permeability varies with scale of a pore network

Project Description

3D Printers are opening up new ways to test geological hypotheses (Hasiuk, 2015). They allow intricate models of porous media to be accurately manufactured from digital designs and thus brought into the "real world" where more common analytical methods (e.g., helium and mercury porosimetry) can be employed (Ishutov et al., 2015). This has been done with increasing fidelity to the original digital designs for porous rocks (Ishutov et al., 2017, 2018).

Laboratory analyses of reservoir rock specimens has been a fundamental technique for defining the quality of subsurface reservoir rocks. However, fluid flow through natural rocks is governed both by the geometry and connectivity of pores, but also the chemistry/mineralogy of their surfaces. 3D Printing is one way to deconvolve these two factors for improved experimental control. This project seeks specifically to test the hypothesis that the permeability of a pore network can be determined by linear regression of permeabilities measured on multiple magnified models of that pore network. This will allow permeability to be measured on samples smaller than could traditionally be analyzed in a laboratory device (e.g., less than a 1-inch cylinder) or samples that could not easily be cored (e.g., a pebble).

Pore geometry models will be 3D printed as 1-inch, 1.5-inch, and 4-inch cylinders using a FormLabs Form3L 3D-printer and analyzed in a helium porosimeter/permeameter. Models will include both simple geometric meshes as well as designs derived from computed tomography on natural pore networks (i.e., reservoir limestones and sandstones).

Deliverables

- Understanding of how scale affects permeability
- Publications and presentations of research results
- 3D-printed models
- 3D-printable models of pore networks (in STL or OBJ format)

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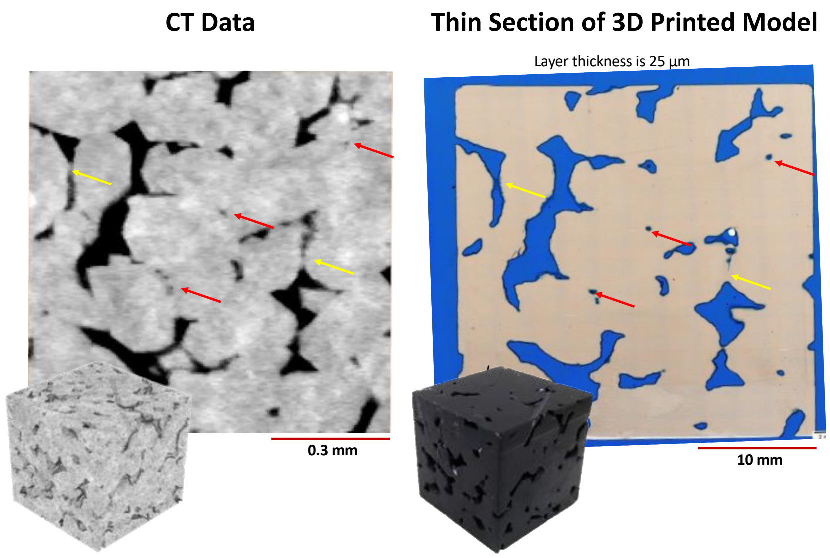

Figure 1*. CT Data and 3D-printed model of CT data magnified by 30x that shows good replication of CT data's pore network (Ishutov et al., 2018).*

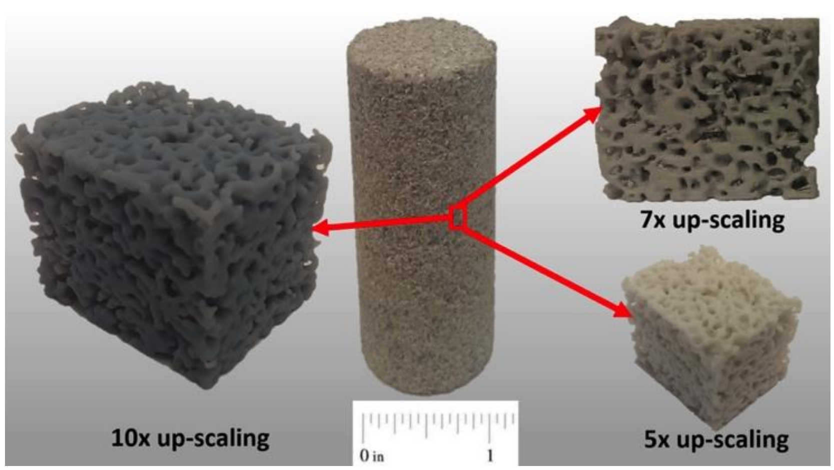

Figure 2*. Three scale models 3D-printed from the same CT data collected on a portion of Idaho Gray Sandstone (Ishutov et al., 2015).*

Impact of Diagenesis on Reservoir Properties of Heterozoan Carbonates

Robert H. Goldstein, Evan K. Franseen, Tony Pugliano, Hassan Eltom

SUBSURFACE APPLICATION: Miocene-Pliocene grainy heterozoan systems in Spain are analogs for Oligocene-Miocene heterozoan reservoirs in the Caribbean, such as the Perla giant gas field (offshore Venezuela), and Miocene heterozoan reservoirs in the Indo-Pacific. Lessons from the outcrops can be applied to other heterozoan reservoir systems in the ancient.
STATUS: Ongoing research; several projects complete
TIMING: Completed and ongoing results available; future projects upon funding
FUNDING: KICC

Purpose

Fundamental differences between heterozoan and photozoan carbonates yield contrasting stratigraphic architecture and original mineralogy. With such differences, it would be expected that low-temperature diagenetic alteration of heterozoan carbonates would yield distributions of petrophysical properties that contrast with those of photozoan carbonates. One might hypothesize that, with the calcite-dominated mineralogies of heterozoans, diagenesis might have less overall impact, preserving aspects of petrophysical properties originally generated in the depositional environment.

Project Description

This study examines porosity and permeability from least-altered Pliocene heterozoan carbonates (Carboneras Basin, Spain), and compares them to diagenetically altered Miocene heterozoan carbonates (Ricardillo area, Spain) to evaluate the impact of low-temperature diagenesis on petrophysical properties. Miocene strata have been impacted by dolomitization associated with ascending freshwater-mesohaline mixing (Li et al. 2013; 2014). Dolomite is concentrated in distal regions and decreases updip and upsection. Dolomite content is correlated with moldic porosity. Later alteration in freshwater (Li et al., 2014) led to calcite cementation and moldic porosity that preferentially affected strata in updip locations.

Methods

1. Fieldwork was conducted at the northern end of Playa de Los Muertos, Cala de la Pelirroja in the Carboneras Basin, Spain and at Cerro de Ricardillo and Cala de San Pedro in the Ricardillo Area, Spain. A total of 11 stratigraphic sections were measured and described at centimeter scale, four from the Miocene of the Ricardillo area, and seven from the Pliocene of the southern part of the Carboneras Basin.
2. A total of 333 thin sections are used for transmitted light and UV petrography to point count grain constituents, point count and measure relative grain size, categorize cements, categorize pore type, and to determine and quantify mineralogy. Miocene samples were stained using Alzarin Red-S and Potassium

Ferricyanide (Lindholm and Finkelman, 1972) to distinguish calcite from dolomite.

3. Background extraction micro-imaging analysis is used to quantify dolomite content for Miocene samples. Diagenetic phases and porosity are quantified and the diagenetic alteration is classified into diagenetic facies.
4. Three hundred sixty-one core plugs were taken parallel to bedding for petrophysical analyses. One hundred eighty-six of the plugs were taken from Miocene deposits, and 175 from Pliocene deposits. Helium porosity, air permeability (Kair), and grain density measurements were taken on each core plug.
5. Diagenetic facies models depositional facies models and petrophysical models were created in Petrel™ to be used as analogs for facies prediction and petrophysical distribution in heterozoan carbonate reservoirs. Altogether, a total 94 8 distinct models were constructed with the following characteristics: (1) all Miocene deposits along Ricardillo; (2) entire Pliocene clinothem from Carboneras; and (3-8) six end-member, lateral depositional profiles forming clinothems in the Pliocene. Each model includes a facies model, porosity model, permeability model, and predictive distribution models for individual lithofacies.

Results and Deliverables

Strata are classified into six diagenetic facies, using amount of dolomitization, dolomite cement, calcite cement, and dissolution. Diagenesis has lowered petrophysical values in Miocene strata compared to least-altered Pliocene (Figure 1), which is due to dolomite and calcite cement being greater than dissolution. For example, least-altered Miocene rudstones have porosity of 40% and 1,888md permeability, whereas diagenetically altered rudstones have 34% and 1,307md. Least-altered Miocene packstones have 43% and 5,131md, whereas diagenetically altered packstones have 30% and 690md.

Strata consist of grain-rich fining-updip clinothems and fining-upward cyclothems. The fining is the result of abrasion and sorting during shoaling to form packstones (sea grass beds are an exception). Rudstones form in slightly deeper water where bioclasts are not abraded and sorted. Diagenetically least-altered cyclothems and clinothems show upward increases in porosity and permeability. Sorted packstones have porosity of 51% and permeability of 6,099md. Rudstones have 42% and 2,537md. After diagenetic alteration, only 46% of the cycles preserve this petrophysical relationship. Packstone facies capping cycles have been altered the most with some moldic porosity and much cementation. It is hypothesized that this results from originally high permeabilities, which provided preferred conduits for diagenetic fluids.

These data have been developed into 3D Petrel™ reservoir-analog models and facies models to aid in predicting the distribution of reservoir character in similar deposits in the subsurface. They yield reservoir analog models capable of storing 26-166 barrels of fluid, some with stratigraphic trapping mechanisms.

Overall, the data show that low-temperature diagenesis has had a negative impact on petrophysical properties in the heterozoan carbonates studied. In contrast to what might be predicted given the calcitic mineralogy of heterozoans, the petrophysical trends developed in the depositional environment are mostly not preserved after low-temperature diagenesis.

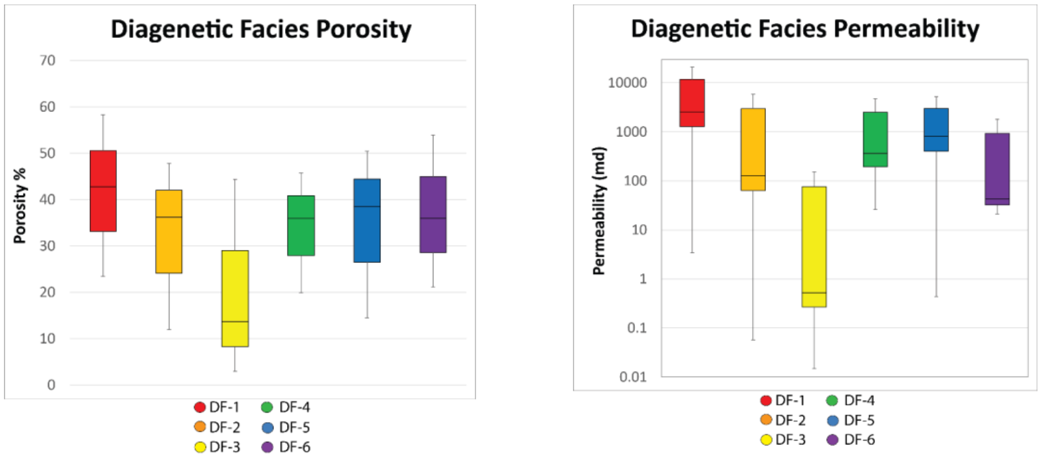

Figure 1. *Box and whisker plots of Miocene and Pliocene petrophysical values. DF-1 (diagenetic facies 1) comprises all Pliocene samples and has the least diagenetic alteration. DF-2 in the least altered of the Miocene with less than 30% dolomite and only minor molds and calcite cement. DF-3 has low dolomite content (<30%) and extensive calcite cement that occludes much of the pore space. DF-4 is entirely dolomitized and has >10% moldic porosity. DF-5 grains have been dolomitized or preserved as abundant molds, but some pores are occluded by both dolomite cement and poikilotopic calcite cement. DF-6 is dominated by replacement dolomite and dolomite cement with little moldic porosity.*

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Grainy Heterozoan Carbonate Reservoir Models

Evan K. Franseen, Robert H. Goldstein, Rachel Dvoretsky, Peter Dillett, Tony Pugliano

SUBSURFACE APPLICATION: Miocene-Pliocene grainy heterozoan systems in Spain are analogs for Oligocene-Miocene heterozoan reservoirs in the Caribbean, such as the Perla giant gas field (offshore Venezuela), and Miocene heterozoan reservoirs in the Indo-Pacific. Lessons from the outcrops can be applied to other heterozoan reservoir systems in the ancient.
STATUS: Ongoing research; several projects complete or in progress
TIMING: Completed and ongoing results available; future projects upon funding
FUNDING: Seeking sponsors

Purpose

Heterozoan carbonates, formed in cool-water or below the photic zone, are abundant in modern subtropical to temperate open shelves around the world, and heterozoan systems may be a better analog for many Paleozoic carbonates than warm-water carbonates (James 1997). Much work has been done on the oil and gas reservoir properties of shallow-water tropical carbonates, but from a comparative standpoint, much remains to be understood about reservoir properties of heterozoan carbonates. We have been studying exceptional 3D exposures of Miocene-Pliocene heterozoan carbonate systems in a variety of basin settings in southeastern Spain for over two decades, and this work has resulted in a better understanding of the depositional controls on these systems. Our recent and ongoing work is focusing on ***development of detailed 3D understanding of stratal geometries, facies distribution, and fluid flow through integration of field, laboratory (including porosity/permeability data) for construction of 3D cellular reservoir analog models to aid in exploitation of grainy heterozoans***.

Project Description

Miocene-Pliocene heterozoan carbonate systems are exceptionally exposed in outcrops of southeastern Spain. Our studies on these exposures show heterozoan systems that developed: 1) in a high-energy, shallow-water ramp setting (Agua Amarga Basin) that developed on gently sloping basement paleotopography; 2) in a deep-water setting (Las Negras area) dominated by transport over highly variable and steep basement paleotopography; 3) in a shaved-shelf system (Carboneras Basin) dominated by lowstand deposition in an area of variable basement paleotopography; 4) in a shallow-water, accommodation-limited setting (Agua Amarga Basin) dominated by deposition during transgression over a wave-planation surface; 5) shallow-water shoaling and fining upward cycles as fundamental depositional units of heterozoan systems.

The status of our progress in understanding the depositional controls and developing reservoir analog models for each of these systems is as follows:

1) High-energy, shallow-water ramp setting (Figure 1) - *Sequence stratigraphy and 3-D reservoir model completed* (Franseen et al., 2005; Dvoretsky et al., 2009). Major controls on the system are relative sea-level changes interacting with gentle substrate slope and

focus of currents. The deposits filled a significant portion of a broad trough-like basinal area and resulted in an overall wedge-shaped geometry and a gently inclined ramp-like surface. Thickest accumulations are proximal to areas focusing currents (providing nutrients).

2) Deep-water setting (Figure 2) - *Sequence stratigraphy and depositional model complete* (Johnson et al., 2005). *3-D reservoir model to be developed in future*. Variable substrate paleotopography resulted in a point-sourced system that focused loose heterozoan grains into deeper water. Strata are primarily composed of coarse and moderate grained intraclastic units interpreted as debris flows, graded facies indicating turbidites, trough cross-bedded packstones indicating tractive currents, and fine-grained hemipelagic deposits. Depositional mechanisms are similar to point-sourced, deep-water siliciclastic reservoirs.

3) Shaved-shelf system - *Sequence stratigraphy and depositional model complete* (Dillett et al., 2003); *3-D reservoir model to be developed in future.* Carbonate deposition was dominated by clinoforms prograding from several areas of gently sloping substrate. Distal deposits typically consist of rhodolite and coarse bivalve packstone and pass updip to structureless bioclastic packstone dominated by relatively well-sorted, fragmented, and abraded grains. A bioclastic packstone in proximal parts of clinoforms was bypassed downslope from shallower water areas. In contrast to tropical systems, sediment deposited at or near sea level does not appear to be preserved.

4) Shallow-water, accommodation-limited setting - *Sequence stratigraphy and depositional model currently being developed* (Hess et al., 2010); *3-D reservoir model to be developed in future*. A thin stratigraphic section of Pliocene heterozoan carbonates was deposited on a sloping marine planation surface at high elevation. Facies consist of abraded, sand-sized carbonate packstones with variable amounts of rhodoliths, oysters, and rounded micrite pebble intraclasts. Overall facies distribution indicates wave-planation terrace margins as locations of preferred carbonate productivity, due to higher energy and increased nutrient input at breaks in slope. Results indicate that the system is dominated by deposition and preservation during transgression.

5) Shallow-water shoaling and fining upward cycles in heterozoan systems – *Sedimentologic recently completed* (A. Pugliano – student); *3-D reservoir analog model*. One Miocene heterozoan system contains stacked, laterally extensive packages of partially dolomitized, shoaling, and fining-upward cycles. Another Pliocene shaved-shelf system is dominated by prograding clinoforms that contain laterally updip, shoaling, and fining-upward facies. These shoaling and fining-upward cycles are a distinctly different depositional pattern from what is generally modeled for photozoan systems, and currently, there are no appropriate reservoir-analog models that propose such a fundamental depositional unit for heterozoan systems. Stratigraphic work and porosity measurements demonstrate that the shoaling upward cycles fine upward because of increased abrasion along wave base. The facies variation produces a predictable distribution of porosity (Figure 3, 4) and permeability values that can be used to populate subsurface geomodels.

Deliverables

Deliverables for the project include maps, stratigraphic sections, cross sections, copies of theses, copies of presentations, quantitative petrography, porosity and permeability data and 3-d cellular reservoir models on the projects and systems that have been completed to date, and those that are currently being studied. Future work will also focus on developing a dynamic fluid flow model and synthetic seismic model for each system to aid in exploration for and production of similar systems in the subsurface.

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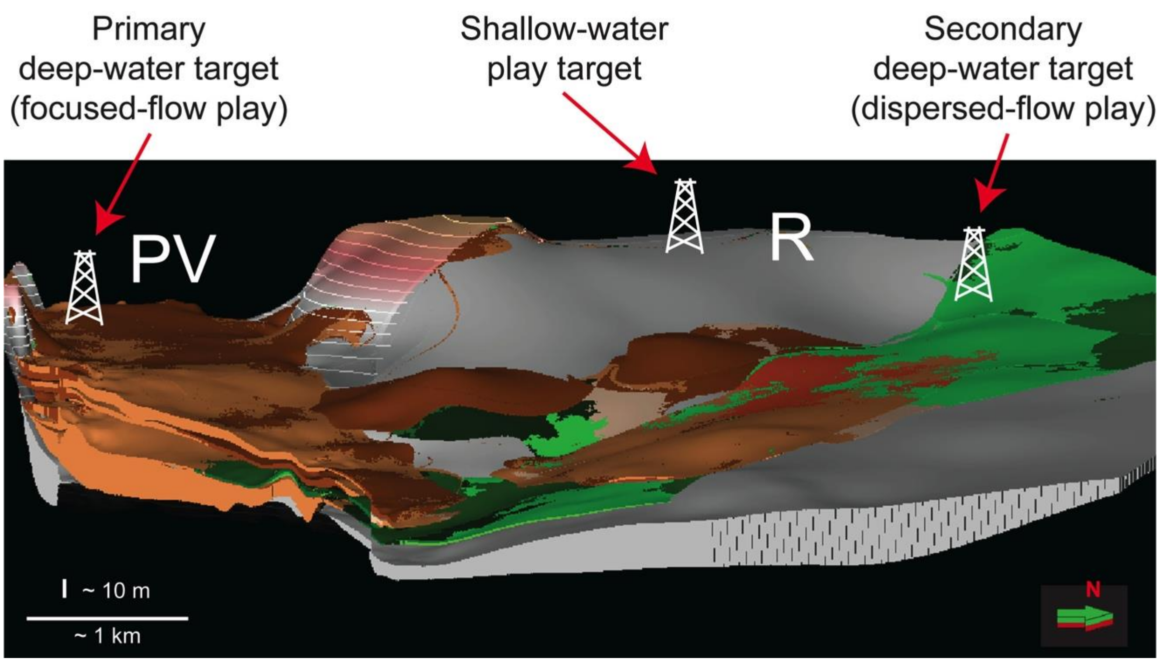

Figure 1. *3-D cellular model developed for Agua Amarga basin. Reservoir targets within the shallow-water heterozoan play are shown in grey (and focused-flow and dispersed-flow deep-water plays for a later photozoan system shown in browns and greens). Shallow-water heterozoan targets are in up-dip locations along the ramp-like surface (R).*

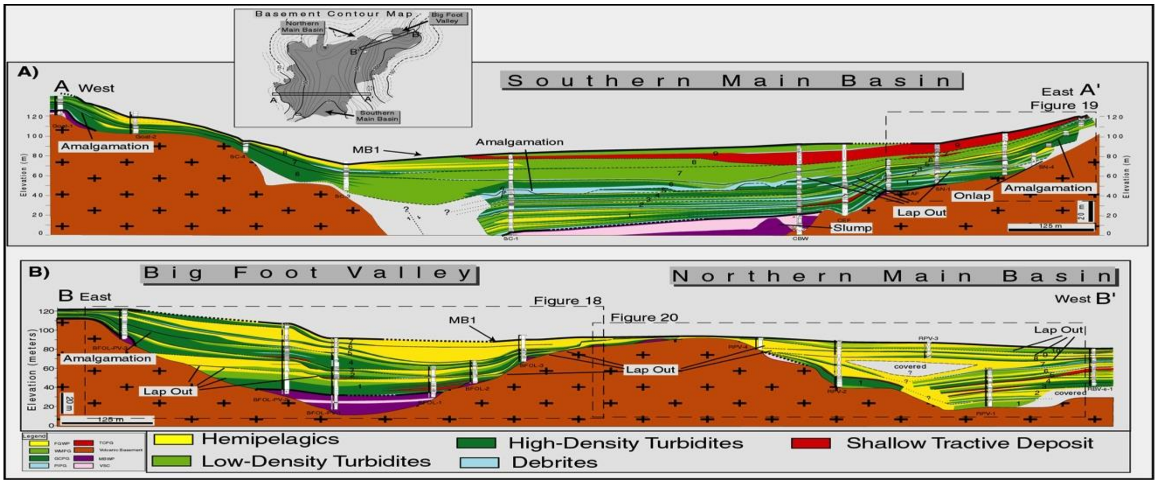

Figure 2. *Point-sourced, deep-water heterozoan carbonates in Las Negras Area.*

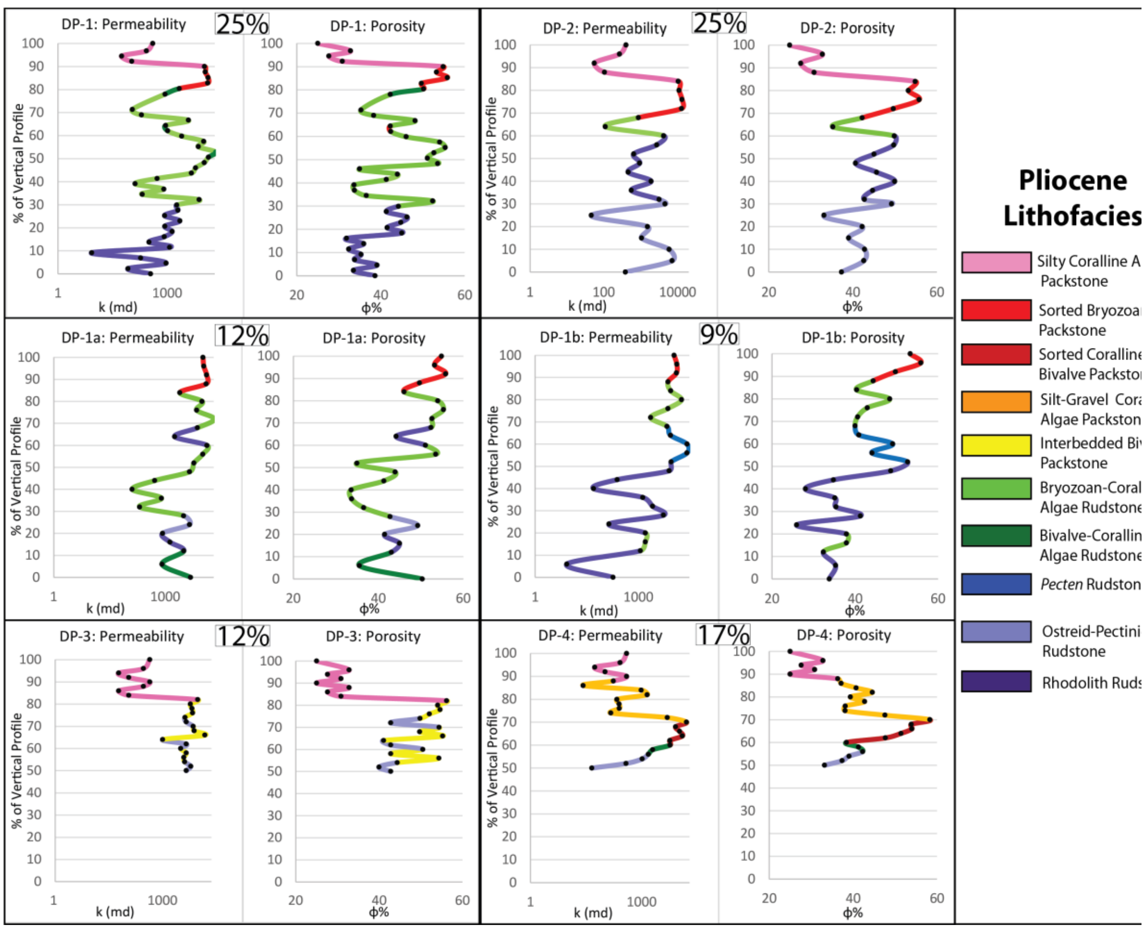

Figure 3. *Porosity and permeability trends associated with shoaling and fining upward in Pliocene heterozoan carbonates (Pugliano, 2015)*

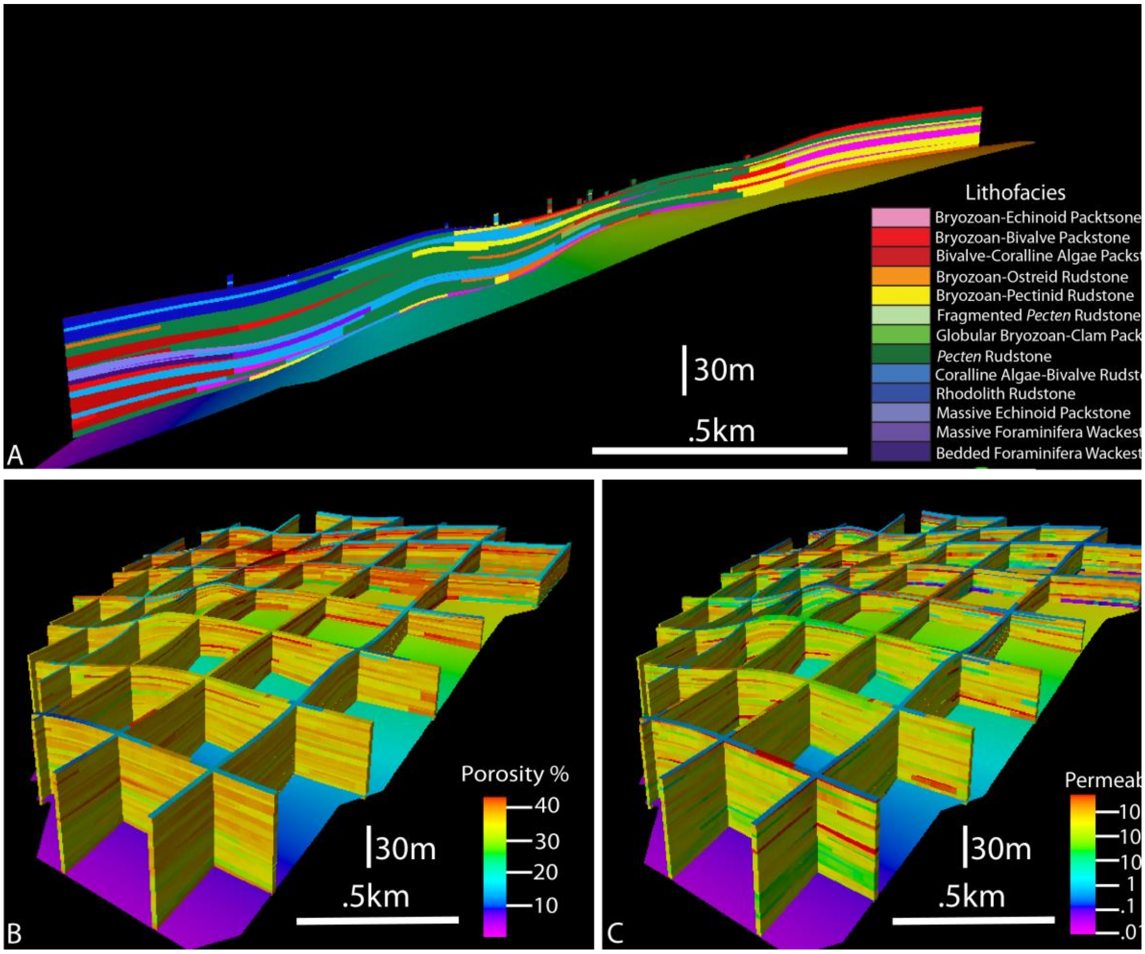

Figure 4. *Static 3D geomodel of reservoir properties in Miocene heterozoan carbonates (Pugliano, 2015)*

Reef and Forereef Slope Reservoir-Analog Models

Evan K. Franseen and Robert H. Goldstein

SUBSURFACE APPLICATION: The outcrops are analogs for highly productive Miocene reservoirs in Southeast Asia, Iran, Iraq, and the Gulf of Suez. Lessons from the outcrops can be applied to other reef and forereef slope reservoir systems in the ancient.
STATUS: Ongoing research; several projects complete and reported to sponsors. Petrel model of one area completed and available to sponsors
TIMING: 2-4 years
FUNDING: Seeking sponsors; software donated by Schlumberger

Purpose

We have been studying exceptional 3-D exposures of Miocene reef systems in a variety of basin settings in southeastern Spain for over two decades, and this work includes quantitative data on the controls for development of the reef systems (Franseen et al., 1998). These data include quantification of relative sea-level history, including rates of rises and falls, accumulation rates, and aggradation and progradation rates for reef systems. An important control on reef development and progradation is paleotopography. Reef systems in this setting include fringing reefs that flank steep sided basement highs that feature aggradation, progradation, and downstepping over 1 km, and reef systems that developed on gently-sloping substrates that feature aggradation, progradation and downstepping for over 2 km.

Our future work focuses on development of detailed 3-D understanding of stratal geometries, facies distribution, and fluid flow in the studied intervals through integration of field, and laboratory data (including porosity/permeability data) for construction of 3-D cellular reservoir analog models to aid in exploitation of subsurface equivalents, such as those in the Indo-Pacific.

Project Description

Miocene carbonate reef systems are exceptionally exposed in outcrops of southeastern Spain, in the Las Negras area. Our studies on these exposures show most developed as complexes that fringed basement highs. Fringing reef complex strata in the Las Negras area superbly display the close association of carbonate fringing reef development and volcaniclastic deposition. The volcaniclastic sandstone and conglomerate wedges exposed in the area are interpreted as marine portions of fan delta lobes that developed marginal to the eroding volcanic islands. Reef and forereef strata are characterized by local preservation of in-place *Porites* framestone, reef talus of mostly slumped *Porites* framestone reef blocks deposited on high-angle, foreslopes, and downlapping foreslope strata consisting of coarse-grained carbonates, fine-grained carbonates or volcaniclastic sandstones/conglomerates.

Reef strata display aggradational to progradational to downstepping geometries that closely tracked the relative changes in sea-level. Autochthonous accumulation of reef strata and development of forereef slopes created steep constructional paleotopography. The early formation of this topography created the slopes on which the youngest reef cycles could step downward during the later period of falling relative sea level. Most phases of reef development are characterized by massive to faintly bedded reef core (1-5 m thick) that grades laterally to talus and forereef slopes with steep (25-35°) clinoforms. The early reefs appear to have prograded (200 - 300 m) with minor aggradation (about 5 m), and the aggradational and largely progradational geometry existed through much of reef development. Later stage reef deposition is characterized by downstepping progradation with successive reef strata formed in topographically lower positions, on the forereef slopes of previous reef cycles, as a result of falling relative sea level. The latest stage of reef development is characterized by clinoforms with steep proximal dips (25 - 30°) that flatten abruptly basinward. This feature is a result of basinward thinning and draping of the flatter topography in basinward locations. These later clinoforms have reef core to distal slope relief of 50 - 90 m over a distance of 300 - 700 m. All stages of reef development reveal abundant reefal material that was transported to foreslopes by mechanisms not necessarily related to sea-level falls. These include turbidity currents, debris flows, and rock falls. It is likely that the apparent rapid production and progradation of the reef itself was a major contributor (self erosion) of reef talus clasts and reefal debris to the foreslopes.

The area adjacent to Las Negras developed one of the more extensive reef platforms in the area (La Rellana platform) that shows various vertical and lateral stages of development over relatively gentle basement paleotopography for approximately 2 kilometers towards the Agua Amarga basin. The La Rellana platform developed in an important drainage divide location for the region that was created by the volcanic substrate. A 2-D cross section exposes the divide and reveals steep basement slope (and resultant steep progradational geometries) dipping towards the Las Negras area to the south, and gentler, more laterally extensive volcanic basement paleotopography (and resultant more extensive and gentler progradational geometries) towards the Agua Amarga basin to the northeast (Figure 2). Therefore, this 2-D La Rellana platform cross section provides an opportunity to determine the role of different paleoslope morphology, and slope dip and direction on evolution of the same platform, as well as providing an opportunity to compare facies, geometries, and sequence development in an extensive platform developed over a gentle substrate paleoslope with equivalent deposits in the Las Negras area that were developed adjacent to steeper sloping substrates. Study of the sequence stratigraphy and depositional controls on the La Rellana platform are completed. An important aspect of that study was tying the La Rellana sequences and facies to equivalent deposits in the adjacent Agua Amarga basin (Sweeney et al., 2015). Many of the basinal facies were sourced from the La Rellana platform; a 3-D cellular reservoir model has already been developed for the Agua Amarga basin (Dvoretsky et al., 2014).

The reservoir analog model project will utilize field data already or currently being collected for the Las Negras and La Rellana areas. That and additional data to be collected, including additional detailed section measuring and facies mapping, and collection of porosity and permeability data, will be integrated to build a 3-D cellular model for each area (Las Negras, La Rellana).

Deliverables

Deliverables for the project include maps, stratigraphic sections, cross sections, copies of theses, copies of presentations, quantitative data that have been completed to date, and those that are currently being studied. Detailed measured stratigraphic sections, tracing on photomosaics, and Lidar data with appropriate overlays of photos, facies, sequences and porosity/permeability distribution. Beyond these data, the project includes routine and special quantitative core analyses on representative samples from each major lithofacies, to characterize the complete range of petrophysical properties and to identify lithofacies-petrophysical relationships, storage, and flow units. Helium porosity, grain density, and air permeability will be measured on not less than 500 samples. These data will be integrated with stratigraphy to generate synthetic seismograms, which will help future explorationists identify similar systems. Finally, a 3-D model of each reservoir analog system (Las Negras, La Rellana) in Petrel™, which will allow future developers the ability to compare reservoirs of similar character and will provide volumetric data.

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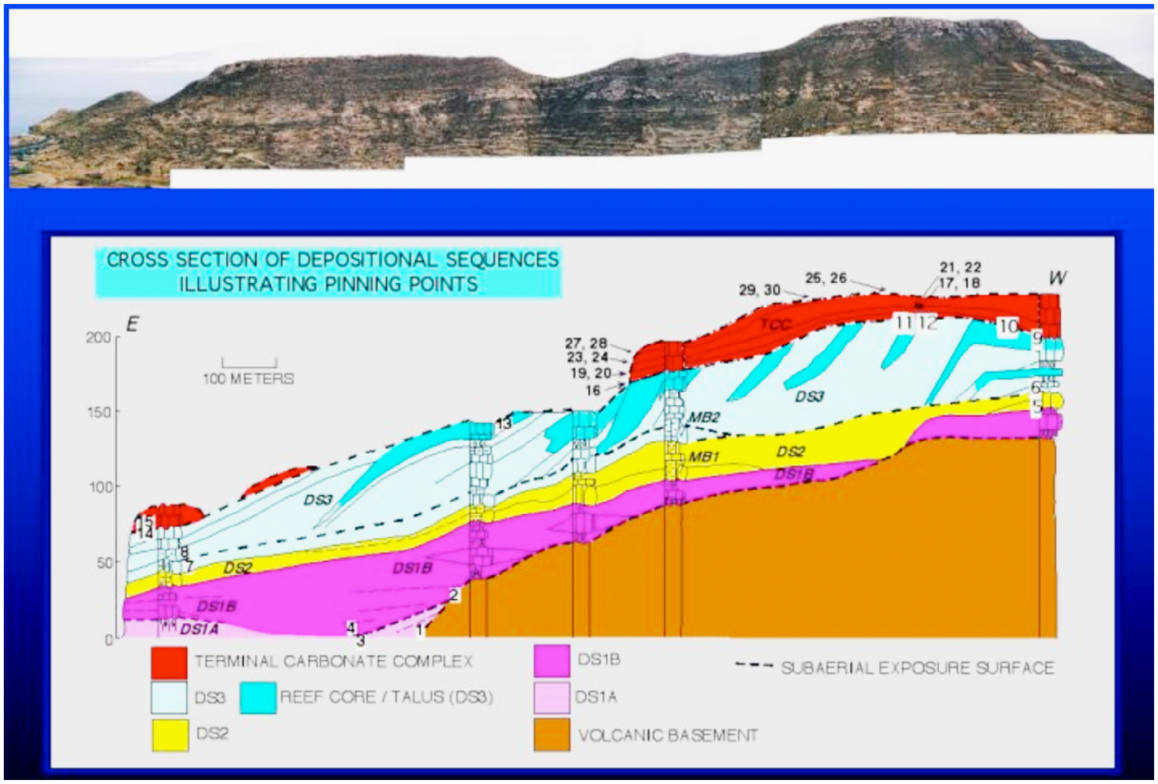

Figure 1. *Fringing reef complex (DS3; blue) in Las Negras area. Scale is in m.*

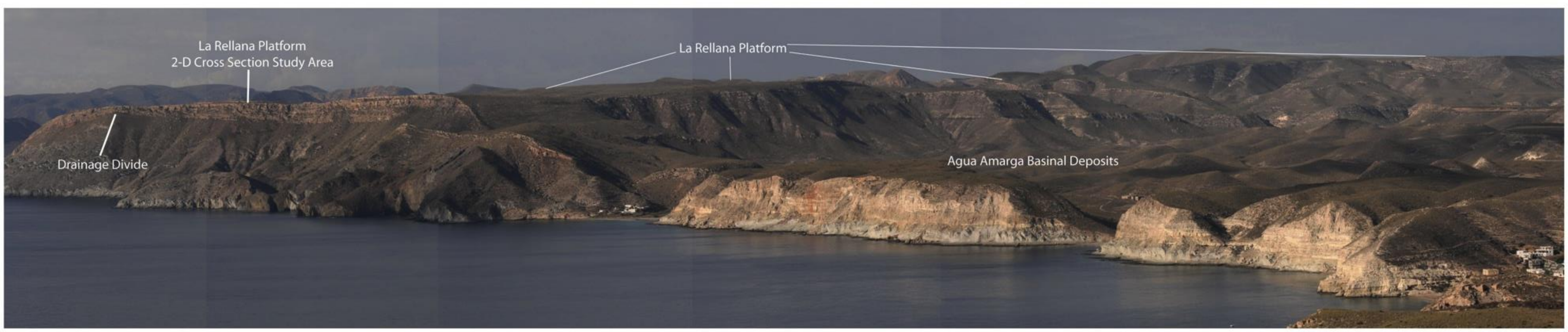

Figure 2. *Oblique aerial photographs showing La Rellana platform study site and relationship to adjacent areas.*

Effect of Bioturbation on Petrophysical Properties of Shelf Carbonates: Part 1: Lateral and Vertical Trends of Preferred Flow Pathways

Hassan A. Eltom and Stephen T. Hasiotis

SUBSURFACE APPLICATION: Hadria, Lower Fadhili, Upper Fadhili and Arab-D Reservoirs, Ghawar Field; Upper Cretaceous Thamama Group and equivalent in the Middle East and elsewhere.
STATUS: Beginning stages of project
TIMING: Project underway
FUNDING: Seeking Funding

Purpose

Although the effect of bioturbation on modifying the rock fabric of the burrow medium is well understood (e.g., Pemberton and Gingras 2005), spatial and temporal variation of such modification, and its effect on lateral and vertical variation of petrophysical properties is less well constrained. Understanding such spatial relationships is important as it has direct implications on understanding reservoir quality of bioturbated carbonate reservoirs. Outcrops of the Tuwaiq Mountain and Hanifa formations in central Saudi Arabia provide a unique setting for the objectives of this study which are: ***1) documenting spatial and temporal variation in Thalassinoides burrow networks of shallow carbonate strata; 2) documenting and understanding the impact of Thalassinoides burrow networks on changing rock fabric and potential preferred flow pathways; and 3) understanding how these preferred flow pathways created by Thalassinoides burrow networks could vary laterally and vertically.*** The results will provide predictions for hydrocarbon exploration and development in terms of understanding trends in petrophysical properties that associated with bioturbated carbonate strata.

Project Description

Trace fossils were identified in the Hanifa Formation according to their architectural and surficial morphologies and fill pattern (e.g., Hasiotis and Mitchell, 1993; Bromley, 1996). Bioturbation intensity of the strata was measured using the ichnofabric index (ii) of Droser and Bottjer (1986) to describe bioturbation and Thalassinoides burrow network intensity in outcrop—ii1 = 0; ii2 = 1–10%; ii3 = 10–40%; ii4 = 40–60%; ii5 = 60–100%; ii6 = >100%—of the Tuwaiq Mountain and Hanifa formations, which was evaluated in the three studied outcrop sections and plotted as vertical profiles.

To construct conceptual and geostatisitical models for facies and ichnofossil index distribution in the field for the study succession, we used recently published data from central Saudi Arabia (Hughes et al., 2008; Eltom et al., 2017, 2018; Fallatah and Kerans, 2017). These studies mapped lithofacies of the Hanifa Formation and the underlying Tuwaiq Mountain Formation in 15 locations and provided lateral and vertical data that are useful for outcrop modeling. We first generated a polygon in Google Earth for the modeling area in central Saudi Arabia, an area that included all the studied sections from previous work. This polygon extends 156 km in the north–south direction, and 130 km in the east–west direction. The polygon was exported to Petrel™2016 as a shape file and was used to construct surfaces for a 3D structural grid of our models. This 3D structural grid consisting of cells of 2D horizontal dimensions of 1 km x 1 km cm, and 160 layers. In this 3D structural grid, four east–west normal faults were inserted on top of locations in the polygon that show wadis (seasonal channels filled with rainfall) in Google Earth. Inserting such structural features in our model provides more realistic visualization and analogy for Hanifa and upper Tuwaiq Mountain reservoirs.

Facies distribution was generated manually (Fig. 1, no algorithms were used) in each layer based on understanding of spatial variation in the field, guided by outcrop data in previous studies (Hughes et al., 2008; Eltom et al., 2017, 2018; Fallatah and Kerans, 2017). Although time consuming, manual construction of facies in the 3D grids ensures the correct distribution of facies and eliminates errors associated with modeling algorithms. Accordingly, the 3D structural grid was divided into 160 stacked 2D layers. Ichnofabric index for each facies was distributed throughout the 3D models using a facies-based distribution. The assignments occurred distinctly for each facies using the Gaussian random function simulation (GRFS) algorithm in Petrel™2016. The ichnofossil index data for this function are the range, the mean, and the standard deviation which comes from our semiquantitative ichnofossil index field data.

Preliminary Results and Deliverables

Shallow to deeply penetrating bioturbation by epibenthic and endobenthic organisms on carbonate shelves can alter the original depositional fabric of carbonate sediments, effectively increasing the overall porosity and permeability in multiple intervals. To explore its impact, and its spatial and vertical pattern, this study examines sedimentologically, ichnologically, and geostatistically, ubiquitous bioturbated strata throughout outcrops of the Middle and Late Tuwaiq Mountain and Jurassic Hanifa formations, in central Saudi Arabia. Each facies and facies association within the study intervals had an ichnofabric index (ii) from nonbioturbated (ii1) to completely bioturbated (ii6). Most important was the occurrence of laterally extensive (>5 km) Glossifungites Ichnofacies, which represent firmgrounds with ii4–6. These Glossifungites Ichnofacies are composed of complex and deep three-dimensional (3D) burrow networks of *Thalassinoides* burrow network (TBN) in mud-dominated lithofacies filled with peloids, skeletal grains, and coated grains. These TBN typically penetrate the entire unit thickness, providing permeability pathways in an otherwise less permeable medium, and interconnects more permeable units above and below firmgrounds, providing vertical connectivity for carbonate strata, and possibly causing stacked plays (Fig. 1). Laterally, the TBN-bearing strata provide reservoir connectivity for otherwise compartmentalized reservoirs in the upper Hanifa strata (Fig. 1). The controls on the spatial and vertical variability of TBN can be attributed to change in water chemistry of the depositional environments, possibly linked to global paleogeographic and paleo-oceanographic conditions.

This phase of the project will provide 3D models that demonstrate how bioturbation and their related permeability could vary laterally and vertically in carbonate shelves. Such a relationship provides predictions for hydrocarbon exploration and development in terms of understanding trends in petrophysical properties that are associated with bioturbated carbonate strata.

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Available upon request

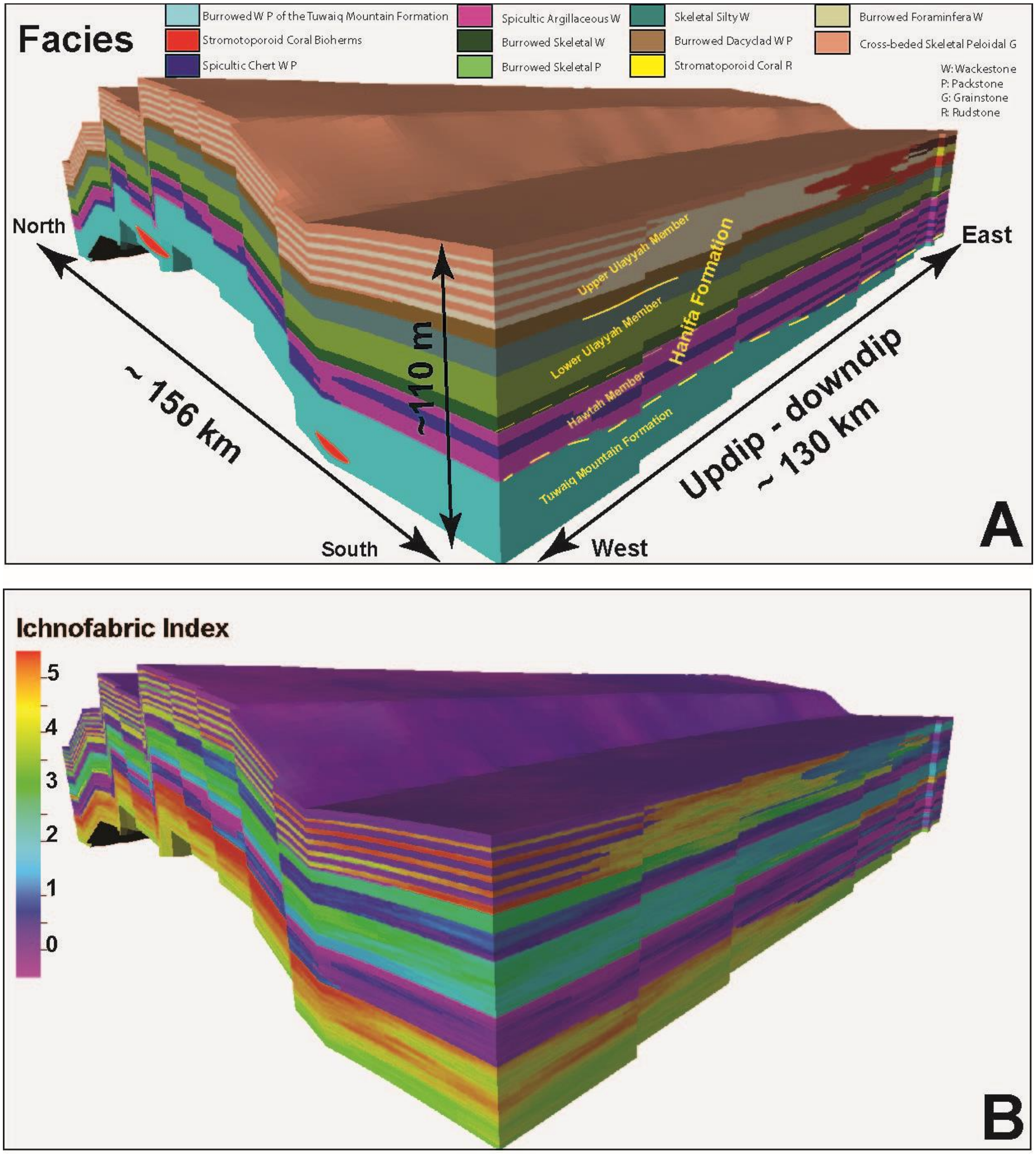

__Figure 1.__ 3D geological and ii models. Note strike direction (north–south direction) and dip direction (east–west direction) of the models. ii values show increase from downdip to updip, and from bottom to top in Tuwaiq Mountain Formation and Ulayyah Member.

Effect of Bioturbation on Petrophysical Properties of Shelf Carbonates: Part 2: Geostatistical Modeling of Burrow Connectivity in 3D Framework

Hassan A. Eltom, Eugene C. Rankey, and Stephen T. Hasiotis

UBSURFACE APPLICATION: Hadria, Lower Fadhili, Upper Fadhili and Arab-D Reservoirs, Ghawar Field; Upper Cretaceous Thamama Group and equivalent in the Middle East and elsewhere.
STATUS: Beginning stages of project
TIMING: Project underway
FUNDING: Seeking Funding

Purpose

Although the notion that burrow connectivity can enhance petrophysical properties of a medium is well established (Pemberton and Gingras 2005; Tonkin et al. 2010; Gingras et al. 2012; La Croix et al. 2012; Baniak et al. 2015; Bayet-Goll et al. 2017; Leaman and McIlroy 2017), quantitative understanding of the relationship between burrow intensity and burrow connectivity is less well constrained. Geostatistical modeling provides one means to enhance understanding of this relationship and ultimately the impact of burrow connectivity on reservoir quality of bioturbated carbonate strata. In this context, ***the objectives of this study are to: 1) qualitatively and quantitatively describe Thalassinoides burrow network (TBN) attributes of outcrops; and 2) integrate these attributes within 3D models (multipoint statistics [MPS], and facies-based permeability modeling.*** The results impact studies of reservoir modeling, flow simulation, and improvement of hydrocarbon exploration and development strategies.

Project Description

To explore how burrow intensity controls burrow connectivity, this study begins with descriptions of outcrops of the Ulayyah Member of the Upper Jurassic Hanifa Formation in central Saudi Arabia (Steineke et al. 1958; Powers et al. 1966; Hughes et al. 2008), in strata dominated by extensive bioturbation. The outcrops provide vertical and lateral 3D exposures that yield a detailed description of sedimentological, ichnological, and stratigraphic features, in an updip–downdip transect. These strata provide a basis for expanding the investigation of the geometrical relationship of the TBN and their medium by use of quantitative 3D modeling. The 3D facies and permeability models for the TBN were constructed using Petrel™2016 through five steps. 1) Collecting observations (e.g., orientation, geometry, connectivity, and intensity of TBN); 2) Constructing a 3D grid that has a 1 m^3 and generating training image for TBN; 3) Generating several 3D TBN models were generated using MPS; 4) Distributing permeability throughout these 3D models using a facies-based method; 5) evaluating connectivity of TBN.

Preliminary Results and Deliverables

At low ichnofossil index (ii) bioturbation intensities (ii2, TBN of 2–10 %, Fig. 1) the 3D models of TBN have many isolated bodies. The largest connected bodies at 2% and 8% TBN intensity represent 28% and 40% of the total burrow volume, respectively. Abruptly at 10% burrow intensity, however, more than 90% of TBN volume is connected (Fig. 1).

At intermediate and high bioturbation intensity (ii3–5, TBN > 10%) each 3D of TBN models consists of one connected volume that represent more than 95% of TBN (Fig 1I, J). Although the models show 90% connectivity in 3D as bioturbation intensity exceeds 10%, the burrow intensities between 10% to 30% suggest isolated burrows in vertical and horizontal planes (Fig. 1A, E), views typical of outcrops and cores.

This project will provide 3D models that show the relationship between burrow connectivity and burrow intensity. These models will help understanding the effective flow in bioturbated carbonate reservoirs.

References

Available upon request

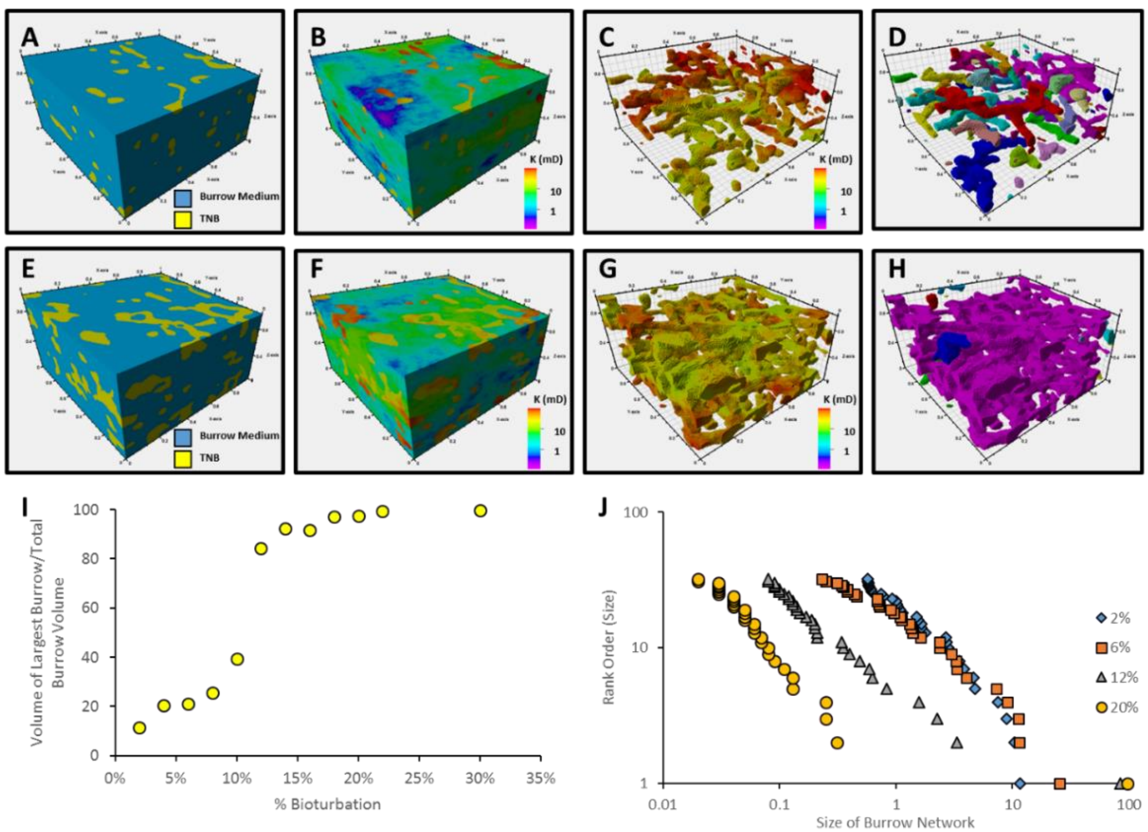

Figure 1. *3D models of TBN shows burrows and matrix (A and E), Permeability models of TBN (B and F), filtered permeability models based on TBN, note the connected permeable volume of TBN (C and G), and connectivity analysis results of TBN with connected cells in the same color (A–D) Burrow intensity of 8%. Note TBN is not fully connected and shows isolated volume. (E–H) Burrow intensity of 20%. Note TBN is more than 95% connected. I) Crossplot shows relationship between bioturbation intensity and volume of largest TBN in 3D models ranges from 2–30% . Note >90% connectivity is established at bioturbation intensity of 12%. J) Crossplot shows relationship between size of TBN and rank order of TBN volume in four levels of bioturbation intensity (2, 6, 12, and 20, 30, and 40%) in logarithmic scale. Note TBN volumes in bioturbation intensity >10% show largest volume >95% and fewer number of volumes.*

Effect of Bioturbation on Petrophysical Properties of Shelf Carbonates: Part 3: Flow Simulation Modeling of Burrow Connectivity

Hassan A. Eltom, Eugene C. Rankey, and Stephen T. Hasiotis

SUBSURFACE APPLICATION: Hadria, Lower Fadhili, Upper Fadhili and Arab-D Reservoirs, Ghawar Field; Upper Cretaceous Thamama Group and equivalent in the Middle East and elsewhere.
STATUS: Beginning stages of project
TIMING: Project underway
FUNDING: Seeking Funding

Purpose

In part 1 and 2 of this study, we demonstrated that *Thalassinoides* burrow networks (TBN) of Glossifungites Ichnofacies could enhance permeability because their coarse-sediment infill provides permeable pathways in less permeable media. High-resolution three dimensional (3D) modeling of these TBN indicated that their connectivity can be established when burrowing intensity reaches 10% and that this connectivity can markedly improve permeability of bioturbated carbonate reservoirs (Eltom et al., 2018). Nevertheless, the impact of burrow connectivity on fluid flow is not well understood. ***This study combines geological modeling, upscaling, and fluid-flow simulation of TBN and less permeable burrow mediums to understand the impact of burrow connectivity on fluid flow.*** The study advances understanding of hydrocarbon productivity in bioturbated carbonate reservoirs by providing prediction on how burrow intensity controls reservoir quality.

Project Description

To explore how burrow intensity controls burrow connectivity, this study begins with descriptions of outcrops of the Ulayyah Member of the Upper Jurassic Hanifa Formation in central Saudi Arabia (Steineke et al. 1958; Powers et al. 1966; Hughes et al. 2008), in strata dominated by extensive bioturbation. The outcrops provide vertical and lateral 3D exposures that yield a detailed description of sedimentological, ichnological, and stratigraphic features, in an updip–downdip transect. These strata provide a basis for expanding the investigation of the geometrical relationship of the TBN and their matrix by use of quantitative 3D modeling. The 3D facies and permeability models for the TBN were constructed using Petrel™2016 through five steps. 1) Collecting observations (e.g., orientation, geometry, connectivity, and intensity of TBN); 2) Constructing a 3D grid that has a 1 m^3 and generating training image for TBN; 3) Generating several 3D TBN models using MPS; 4) Distributing permeability throughout these 3D models using a facies-based method; 5) evaluating connectivity of TBN.

Preliminary Results and Deliverables

The geometrical details of the TBN change considerably through the sequential upscaled models. Whereas the fine grid models preserved the geometrical details of the TBN, the coarse grid models show homogenization between the TBN and medium. Upscaled model US4 has the lowest cell number that preserves the geometry of TBN, and was selected for flow simulation runs. The fluid flow simulation on upscaled model US4 revealed three relationships between flow rate and TBN intensity (Fig. 1): 1) Models with TBN < 10% have unpredictable flow rate based on burrow intensity (Fig. 1). 2) Models with TBN from 10% to 50% (Fig. 1) have flow rates that increase with burrow intensity (Fig. 1). 3) Models with TBN > 50% have flow rate increase with burrow intensity but with lower rate of increase than in TBN between 10% to 50% (Fig. 1).

This project will provide 3D models that show the relationship between burrow connectivity, burrow intensity and flow properties. These models will help understanding the effective flow in bioturbated carbonate reservoirs.

References

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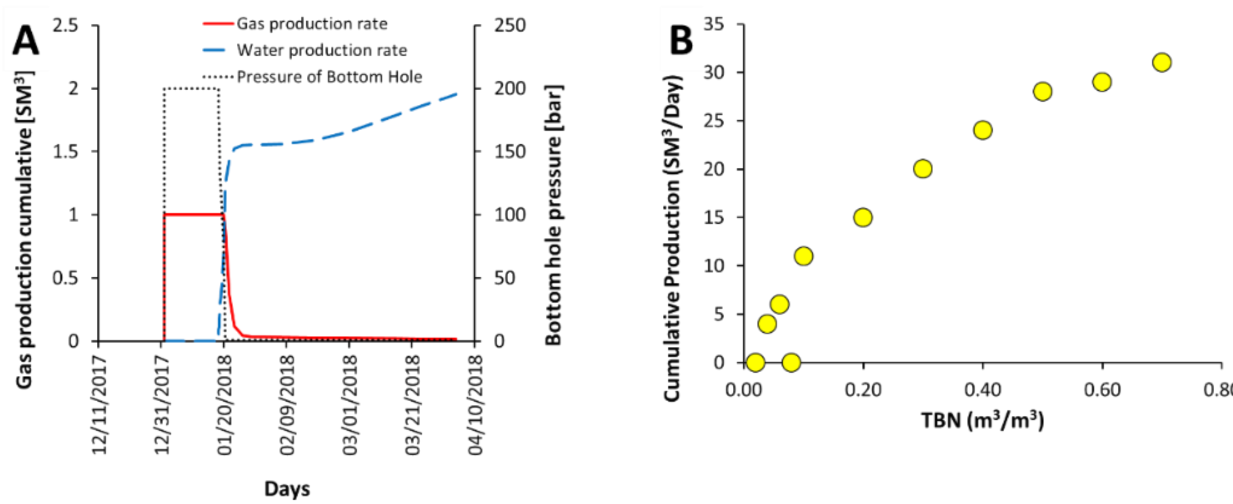

Figure 1. *A) Example of simulation results in which water breakthrough define the end of gas production and drop of bottom hole pressure. B) Cumulative gas production through time plotted based on TBN percentages. Note that gas production increase with TBN percentages.*

Effect of Bioturbation on Petrophysical Properties of Shelf Carbonates: Part 4: Permeability Estimation from Well Testing: Approach to Determine Appropriate Flow Properties for Bioturbated Reservoirs

Hassan A. Eltom, Stephen T. Hasiotis, Eugene C. Rankey, and Reza Barati

SUBSURFACE APPLICATION: Hadria, Lower Fadhili, Upper Fadhili, and Arab-D Reservoirs, Ghawar Field; Upper Cretaceous Thamama Group and equivalent in the Middle East and elsewhere.
STATUS: Beginning stages of project
TIMING: Project underway
FUNDING: Seeking Funding

Purpose

One way to overcome the gap between laboratory measurements of permeability on individual burrows and the actual reservoir permeability of bioturbated carbonate is to calculate flow capacity over average rock volume of distinct burrow morphologies and intensities, or what is defined as permeability-thickness (kh). Well testing can provide means to estimate kh in real reservoir conditions, and, therefore allows for better prediction of flow properties based on burrow intensity. In this context, ***the objective of this study is to estimate permeability of bioturbated strata from dynamically measured flow rate and pressure drop (from well testing) in simulated models that consists of a range of burrow morphologies and intensities of bioturbated mud-dominated carbonate***. Our ultimate goals are to provide a workflow that can relate permeability thickness to burrow morphology and intensity in strata with coarse permeable burrow infill. Such understanding can produce predictive models on reservoir performance of bioturbated strata and can be useful for reservoir modeling.

Project Description

The permeability of mud-dominated carbonate is usually low (> 2 mD, e.g., Lucia, 1985). Coarse sediment reworking by biological activities commonly results in enhanced permeability of sediments and, therefore, the effective flow of mud-dominated, consolidated carbonate (Pemberton and Gingras, 2005; Gingras et al., 2012; La Croix et al., 2012; Baniak et al., 2015; Bayet-Goll et al., 2017; Leaman and McIlroy, 2017). This enhancement depends on burrow connectivity that increases with burrow intensity and depends also on burrow morphology (La Croix et al., 2012; Baniak et al., 2015; Eltom et al., 2018). For example, a well-connected framework of *Thalassinoides*, which is characterized by boxwork, three-dimensional morphology, can be established at burrow intensity < 12% (Eltom et al., 2018). Such framework can be essential for effective flow of mud-dominated facies because the coarse-sediment infill of *Thalassinoides* in firmground provides permeable pathways in otherwise less permeable media (Pemberton and Gingras, 2005; Gingras et al., 2012).

For these coarse sediment infill, laboratory measurements (e.g., spot-permeability measurements) can provide a rough estimation of permeability, however, modeling these permeability values in subsurface grids represents a major challenge for reservoir geologists. This challenge may be related to scale differences between the grid cell of subsurface reservoirs and the individual burrow in which these measurements have been conducted. For example, in reservoir modeling, a grid cell could range from 50 m to 1000 m and may reach three orders of magnitude larger than the diameter of any individual burrow (range from 0.5 cm to 5 cm). This grid cell should be assigned one single value of permeability, despite that the rock mass it represents may consist of mixed permeable burrow fills and impermeable burrow medium. Assigning permeability of the burrow fill alone to the grid cell would result in overestimation of the overall permeability of the modeled reservoirs, whereas assigning burrow medium or the average permeability of the burrow fill and burrow medium to the grid cell would result in an underestimation of the effective flow of the modeled reservoirs. Thus, the appropriate permeability values to use for modeling bioturbated reservoirs to understand their effective flow remains unclear. Yet, understanding the effective flow of such reservoirs is essential to enhance their hydrocarbon production.

This study will use geostatistical and fluid-flow modeling to simulate multiple modeling scenarios of different types of burrow morphologies in bioturbated reservoirs in which flow rate depends on burrow intensity. From these multiple modeling, kh will be calculated using pressure build-up approach, and related to burrow intensity. Such relationships provide predictive on reservoir performance of bioturbated strata and can be useful for reservoir modeling.

Expected Results and Deliverables

This research project will also deliver multiple flow simulation scenarios of the *Thalassinoides* burrow networks and host medium of the Glossifungites Ichnofacies. These models will help assess how geological heterogeneity in bioturbated carbonate influence hydrocarbon flow and production, and will provide estimate for permeability thickness, which will help modeling effective flow of bioturbated carbonate.

References

Available upon request

Comparative Ichnology of Pleistocene, Holocene, and Modern Carbonate Shoreface Deposits: A Predictive Ichnofacies Model and Effect on Rock Properties

Alexa Goers, Steve Hasiotis, and Gene Rankey

SUBSURFACE APPLICATION: Understanding the influence of biota in modifying carbonate textures, porosity and permeability. Results should be broadly applicable, but most directly to shallow carbonate shoreface reservoirs, such as the Jurassic Smackover Formation or Jurassic of the Middle East
STATUS: Focused-term project nearing completion
TIMING: Significant results available to membership this year
FUNDING: Partial from consortium

Purpose

Burrowing organisms can markedly alter depositional sedimentary textures, diagenesis, and petrophysical characteristics of carbonate strata. Although descriptions of carbonate successions commonly refer to bioturbation, quantitative data on spatial variability of ichnodiversity and ichnofabrics are rare (e.g., Goldring et al. 2005). Furthermore, few studies focus on the influence of biogenically modified sedimentary fabrics on reservoir quality (e.g., Pemberton & Gingras 2005; LaCroix et al. 2012). To address this issue, this study characterizes ichnologic and sedimentologic variability in Pleistocene, Holocene, and modern carbonate shoreface deposits. The purpose of this study is ***to evaluate trace fossil associations and ichnofabrics within carbonate shoreface environments to produce a conceptual ichnofacies model***, and as a secondary goal, ***to explore the effect of bioturbation on permeability pathways and porosity***.

Project Description

Comparative analyses of ichnologic and sedimentologic trends in Pleistocene, Holocene, and modern shoreface deposits provide quantitative information on the controls of trace fossil distribution and preservation in carbonate strata. Integration of field observations with spot-minipermeameter, petrographic, and image analysis data provide a means to assess the effect of burrowing organisms on carbonate depositional textures.

This study focuses on Pleistocene and Holocene outcrops and modern shoreface deposits on the western, leeward margin of Crooked Acklins Platform, southern Bahamas (CAP). CAP islands are composed of Pleistocene and Holocene reef, shoreface, and backshore deposits that form shore-parallel topographic ridges. The present-day shelf is 500–2,200 m wide, has an arcuate trend, and gently slopes (<0.5°) to a depth of up to 31 m before the drop off. CAP is influenced by southeasterly trade winds, yet storm-associated waves from the W–NW are the strongest hydrodynamic influence on the leeward margin.

Variability in Pleistocene, Holocene, and modern deposits is captured through integration of outcrop analyses with assessment of traces and sediments on the present-day shelf. Four transects on the extant seafloor record biota and traces with variability of bottom conditions, sediments, and geomorphic elements. Petrographic analyses quantify trace-fossil influence on grain type, size, sorting, and cement type and abundance. Image analysis of photomicrographs provides point count data for grain constituents, cement abundance, and percentage of porosity.

Preliminary results illustrate that ancient and modern deposits show similar along-strike variations in grain type, size, and sorting, as well as degree of bioturbation, ichnodiversity, and burrow depth. Sedimentologic and ichnologic variability on the leeward margin of CAP are interpreted to reflect proximal-to-distal and along-strike variations of depositional energy. Preserved porosity of Pleistocene samples ranges from 2.5–27.9%, and permeabilities range from 0.023–220 Darcys. Petrographic analysis reveals that mm-scale horizontal burrows (e.g., *Planolites*) are characterized by greater porosity than the matrix, as burrow interiors have little to no internal cement. Spot-minipermeameter data reveals that cementation patterns associated with biogenic modification of sedimentary fabrics can result in alteration of permeability by up to 2 orders of magnitude.

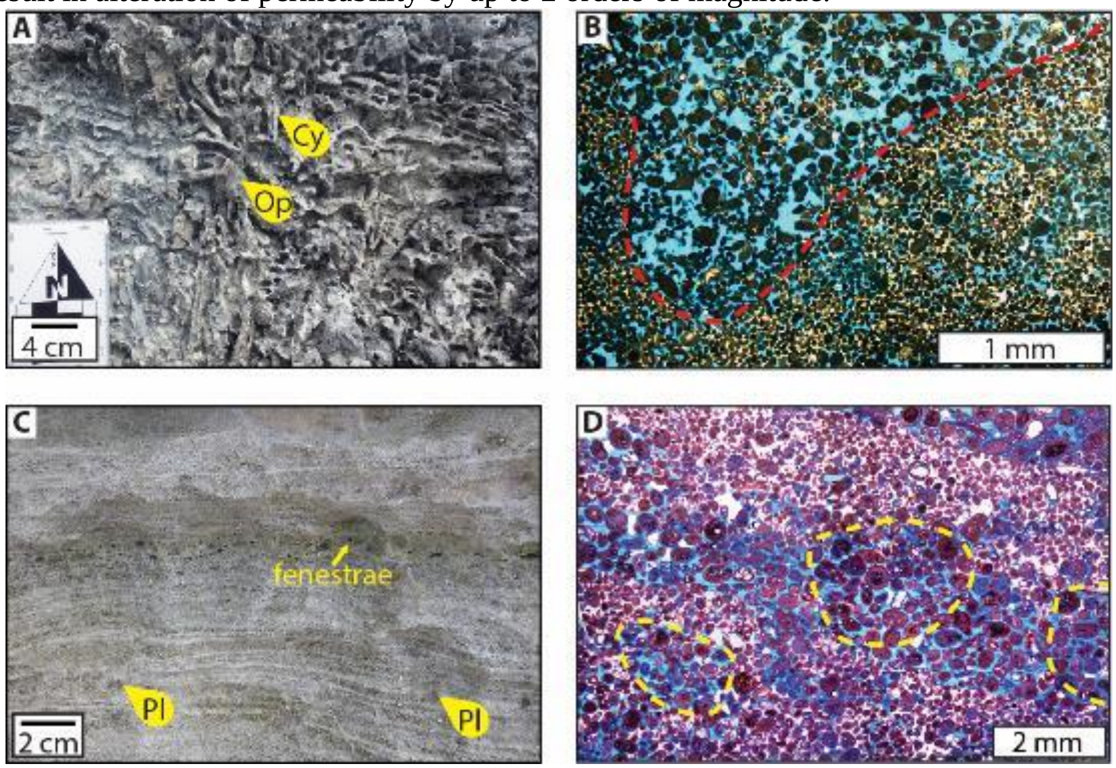

***Figure 1**. Representative traces of Pleistocene shoreface deposits in outcrop and thin section. A) Vertical, cement lined burrows in cross-stratified, moderately sorted, medium sand peloid-ooid-composite grainstone with ichnofabric index (ii) 4. B) Thin section photomicrograph of A, illustrating coarser, poorly sorted burrow fill with less internal cement than the matrix. C) Horizontal burrows in plane laminated, peloid-ooid-skeletal grainstone with fenestrae and ii 3. D) Thin section photomicrograph of C, illustrating coarse-fine laminae with blocky calcite cement, modified by mm-scale horizontal burrows. Note decreased cement in burrow interior. Cy=*Cylindrichnus, *Op=*Ophiomorpha, *Pl=*Planolites.*

Deliverables

This study examines the nature and distribution of trace fossils within carbonate shoreface strata to establish the relationship between ichnology, diagenetic processes, and petrophysical characteristics. Results of this study will integrate trace-fossil associations of sedimentary facies with field and lab data to produce a conceptual ichnofacies model specific to carbonate shoreface systems. This model will aid in understanding and predicting the distribution and effects of biogenic modification on strata and porosity and permeability within similar ancient carbonate systems.

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Flow Properties of Vuggy Carbonate Strata: Phase 1 - The Relationship between Vug Connectivity and Vug Fabric: Geostatistical Simulation to Understand Effective Flow in Vuggy Carbonate Reservoirs

Hassan A. Eltom, Eugene C. Rankey, Robert H. Goldstein, Reza Barati

SUBSURFACE APPLICATION: Ordovician Tahe Reservoir, a carbonate, naturally fractured reservoir in western China; Eocene Reservoirs in Wafra Fields Kuwait/Saudi Arabia; Eocene El Garia and Jdeir Formations reservoir Gulf of Gabes–Tripoli, offshore Tunisia and Libya; Eocene Rus Formation reservoir in Qatar; Intra-salt reservoirs, Late Neoproterozoic to Early Cambrian Ara Group, South Oman Salt Basin; Reservoirs in Arbuckle Group Midcontinent United States of America; Carbonate reservoirs in Kenkiyak pre-salt oilfield, Kazakhstan; Vuggy reservoirs in pre-salt Kwanza Basin, offshore Angola
STATUS: Initial work being done
TIMING: Study in progress, significant results to be reported
FUNDING: KICC and Equinor

Purpose

Vugs can be classified into two general classes – separate vugs and touching vugs (Lucia, 1995). Separate vugs can be fabric selective, can occur within particles or expand beyond a particle, and are interconnected only through the matrix porosity (Lucia, 1995). Touching vugs can also expand beyond the particle size, but in contrast to separate vugs, they form an interconnected pore network. These distinct styles of interconnectivity imply that simply increasing the volume and number of separate vugs does not necessarily increase permeability, whereas increasing touching vugs could potentially increase permeability greatly (Lucia, 1995). These general patterns of vug connectivity have been applied to relate carbonate fabrics to the petrophysical characterization of vuggy carbonate, and ultimately enhance understanding of their reservoir quality. Nevertheless, controls on connectivity of vugs and how separate vugs can become connected is not well understood. What’s more, it is unclear what amount and pattern of connectivity of vugs creates high-permeability pathways that bypass most volumes, or overall high permeability that access most volumes.

To address these critical questions, ***the objective of this study is to test hypotheses that connectivity of vugs is related to vug shape, size, abundance, and spatial distribution.*** To test these hypotheses, this study simulates ranges of hypothetical vug attributes in high-resolution three-dimensional (3D) geocellular models, and evaluates their effect on vug connectivity through advanced statistical analysis. The results provide essential quantitative insights on the relationships between vug fabrics and vug connectivity. These findings will have pronounced impact on understanding the factors that determine the effective flow of hydrocarbons within vuggy carbonates.

Project Description

The hypotheses of this study will be tested by simulating ranges of variables —shape, size, abundance, and spatial distribution of vugs—in high-resolution 3D geocellular models.

These variables are designed as variables that control vug connectivity (the dependent variable), which was expressed by the largest volume of vugs (LV) in each geocellular model. Analysis of variance (ANOVA) and multiple linear regression analysis will be run to understand the relationship among the independent and the dependent variables.

Expected Results and Deliverables

Tens of 3D models with hypothetical vug attributes will be available to evaluate the relationship between vug fabric and vug attributes. Outcome of these models will be used as input for statistical analyses to develop statistical models that can predict the connectivity of vugs in terms of their LV in vuggy carbonate reservoirs, which ultimately provide prediction for effective flow in vuggy carbonates.

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Flow Properties of Vuggy Carbonate Strata: Phase 2-Feasibility Study on Well Data and Flow Modeling to Produce Scenarios of Vuggy Porosity Connectivity and Effective Flow

Hassan A. Eltom, Reza Barati, Robert H. Goldstein, Eugene C. Rankey

SUBSURFACE APPLICATION: Ordovician Tahe Reservoir, a carbonate, naturally fractured reservoir in western China; Eocene Reservoirs in Wafra Fields Kuwait/Saudi Arabia; Eocene El Garia and Jdeir Formations reservoir Gulf of Gabes–Tripoli, offshore Tunisia and Libya; Eocene Rus Formation reservoir in Qatar; Intra-salt reservoirs, Late Neoproterozoic to Early Cambrian Ara Group, South Oman Salt Basin; Reservoirs in Arbuckle Group Midcontinent United States of America; Carbonate reservoirs in Kenkiyak pre-salt oilfield, Kazakhstan; Vuggy reservoirs in pre-salt Kwanza Basin, offshore Angola
STATUS: Proposed project
TIMING: Proposed project
FUNDING: KICC and Equinor

Purpose
Well logs and laboratory measurements of core plugs or whole core (routine core analysis) provide fundamental information for assessing petrophysical properties of carbonate reservoirs, and ultimately to evaluate their fluid flow properties. However, such measurements can lead to inaccurate assessment of effective reservoir-flow properties of vuggy carbonates because of the inherent multiscale heterogeneity of vugs and vuggy strata. ***This project aims to quantitatively address questions regarding controls on flow properties of vuggy carbonate strata from one subsurface example through characterization of vug distribution, vug attributes, and what controls the relationship between vug fabric and flow properties.***

Project Description
This project will explore important geological and geometric parameters (area, aspect ratio, abundance, shape) of vugs from image logs, petrophysical measurements and reservoir performance from five wells. Such parameters can help understanding vug connectivity based on the models that we developed in Phase 1 of this study. Applying the vug attribute-connected volume relations developed in Phase 1 to data from these wells provides a means to predict connected volumes in the reservoir, which will eventually provide understanding for effective flow. Phase 2 (this project) will develop multiple models that represent different simulation case scenarios of: 1) vugs and non-porous matrix; and 2) vugs and porous matrix. Data for the porous matrix scenarios will use laboratory measurements of porosity and permeability from core plugs. In the final stage of the project we will conduct fluid flow simulation on these models to history-match reservoir performance in terms of its effective flow.

Expected Results and Deliverables
- Characterization of vugs from one reservoir in 5 wells
- Upscaling workflow from image logs to 3D models of vug distribution

- Workflow for flow simulation of vuggy reservoirs with matrix permeability
- Match between modeling results and reservoir performance and properties to predict production – it is expected that some vugular intervals will host high-permeability zones with well-connected vugs and others will house more isolated vugs
- Analysis of geologic control on vug distribution – it is expected that some intervals will be best modeled by stochastic models whereas other intervals will be best modeled using multipoint statistics that force vug geometry

Flow Properties of Vuggy Carbonate Strata: Phase 3 – Geologic Controls on Properties of Vuggy Carbonates and Impact on Fluid Flow

Hassan A. Eltom, George Tsoflias, Robert H. Goldstein, Eugene Rankey, Reza Barati

SUBSURFACE APPLICATION: Ordovician Tahe Reservoir, a carbonate, naturally fractured reservoir in western China; Eocene Reservoirs in Wafra Fields Kuwait/Saudi Arabia; Eocene El Garia and Jdeir Formations reservoir Gulf of Gabes–Tripoli, offshore Tunisia and Libya; Eocene Rus Formation reservoir in Qatar; Intra-salt reservoirs, Late Neoproterozoic to Early Cambrian Ara Group, South Oman Salt Basin; Reservoirs in Arbuckle Group Midcontinent United States of America; Carbonate reservoirs in Kenkiyak pre-salt oilfield, Kazakhstan; Vuggy reservoirs in pre-salt Kwanza Basin, offshore Angola
STATUS: Initial work being done
TIMING: 2019-2021
FUNDING: KICC and Equinor

Purpose

This project aims to quantitatively address questions regarding ***controls on flow properties of vuggy carbonate strata***. In Phase I, we propose to start with modeling impact of vug shape, size, and distribution on development of touching versus isolated vugs as a means of modeling controls on development of permeability pathways that either bypass or engage reservoir volumes. In Phase 2, we apply these models to a subsurface example and develop workflows for flow simulation. In Phase 3 (this proposal), we develop a casebook of vug distribution, classified by geologic control, from outcrop analogs. One example will be run through the fluid flow simulation workflow to predict behavior. This example will be tested in the field using geophysical techniques. On the basis of its results, model workflow will be refined.

Project Description

This project will gather real-world data of vug attributes from 2-D outcrop and core photographs, well logs (FMI and sonic scanner), remote sensing data, or other metrics from previous KICC studies and the literature. These vug attributes are already in various stages of data acquisition from the KICC repertoire and include the following geologic settings: (1) long-term regional paleokarst (e.g. Mississippian-Pennsylvanian and Lower-Middle Ordovician); (2) small-scale stacked paleokarst (e.g. Cretaceous of Mexico), (3) hypogene/hydrothermal vugs (e.g. Las Negras, Upper Mississippian Tri-State MVT district); (4) fracture control (Rus Formation, Saudi Arabia); (5) solution-enlarged molds in reefs (Cretaceous Pipe Creek, Miocene of Spain); (6) solution-enlarged after evaporite nodules; (7) burrow control; (8) "swiss cheese" karst (Pliocene of Spain); and (9) vugs in microbialite (modern and Ordovician). The real-world data will be used to populate 3D training images to form a casebook of geologic controls on vug distribution and implementation of flow simulations using the workflows generated in Phases 1 and 2.

This will be followed by a proof-of-concept actual flow test to evaluate or validate flow model realizations using experimental geophysical means. For example, time-lapse ground penetrating radar (GPR) and electrical resistivity imaging will monitor injected tracers in a representative vuggy carbonate outcrop to provide reservoir scale (10s of meters) flow properties.

Deliverables

- Casebook of examples of vuggy carbonates categorized by geologic control
- 3D training images applicable to various geologic scenarios
- A geophysical test of various realizations of model simulation

Digital Rock Physics of KICC Carbonate Formations

Arsalan Zolfaghari, Amirmasoud Kalantari
Co-PI: Shahin Negahban, Robert Goldstein

SUBSURFACE APPLICATION: Carbonate and siliciclastic rocks
STATUS: Focused-term project in progress
TIMING: To be completed in the future
FUNDING: Full from a KICC proposal

Purpose

The purpose of this project is to prepare a Digital Rock Physics (DRP) catalog for carbonate formations that interest Kansas Interdisciplinary Carbonate Consortium (KICC) members. We propose to develop a DRP workflow for predicting the main petrophysical properties from tomographic 3D images of carbonates. The proposed catalog will include simulated petrophysical properties and 3D models (i.e., rock's interior structures, pore space, and representative pore networks) of a wide range of carbonate samples. We start with porosity and then move to flow-related properties (i.e., permeability and relative permeability). The process will get more complex for the flow-related properties, e.g., permeability, relative permeability, and capillary pressures. Modern microscopic imaging and advanced simulation techniques will be used in this project.

Project Description

The DRP technology could potentially result in significant cost reductions and reliability improvements by predicting the main petrophysical properties and providing physical insights into pore-level phenomena. Over the last 15 years, pore-scale imaging and modeling techniques have been developed as a predictive tool for providing services to the oil and gas industry. Therefore, the Department of Chemical and Petroleum Engineering and KICC at the University of Kansas (KU) are pursuing this technology by housing a powerful helical micro-CT imaging system which produces unsurpassed image fidelity at pore levels [Zolfaghari and Negahban, 2020]. The acquired images will be analyzed by segmenting the resolved pore space, calculating porosity and permeability, simulating mercury primary drainage, analyzing pore space connectivity, extracting representative pore networks, and estimating pore space contribution of the microporosity regions (i.e., unresolved pore space). The latter would significantly impact the estimation of porosity and pore connectivity in carbonates where wide pore size distributions constitute the very fabric of the pore space. The goal of this project is to document a complete workflow of the DRP technology applicable to the carbonate formations that interest KICC members. This includes sample preparation, image acquisition, image processing, computational mesh generation, and image simulations.

A wide pore size distribution is hypothesized for the carbonate samples of this project. Therefore, we will pay close attention to the sample size and image resolution. This is because the 3D images should be larger than the Representative Elementary Volume (REV) and have high enough resolution to capture smaller pore sizes. This is aligned with the outline of other KICC's prospectuses focusing on the characterization of the microporosity regions. See KICC's prospectuses entitled: "An Integrated Approach for a Closed-Loop Microporosity Characterization" and "Experimental Characterization of the Microporosity under Multiphase Flow Conditions". The former proposes a physics-based pore-scale network model (PSNM) [Zolfaghari and Piri, 2017 a, b] to address the impact of microporosity on porosity and pore space connectivity [Hakimov *et al.* 2018 a, b]. The latter, however, proposes a systematic pore-scale experimental investigation of two-phase oil/brine flow in a carbonate sample with wide pore size distributions. The KICC offers a complete range of DRP services for characterizing microporosity by providing a platform to link the results of different proposed projects. For instance, in this project, we propose to image several sizes of carbonate samples at different resolutions and populate our findings from the high-resolution to the low-resolution images. These results can then be used directly in other KICC's project (e.g., PSNM or experimental investigation of microporosity as explained above). Please see KICC's prospectus entitled "An Integrated Approach for a Closed-Loop Microporosity Characterization" and "Experimental Characterization of the Microporosity under Multiphase Flow Conditions" for more details.

Deliverables

The DRP catalog for carbonates will include the following data:

1. 3D tomograms of the rocks demonstrating the interior structure of the rocks,
2. Extracted pore space in 3D after segmenting connected and isolated clusters,
3. Representative pore network for the connected pore space,
4. Detailed analyses of the pore space including porosity profiles, pore size distributions, isolated cluster size distributions, and pore shapes, and
5. Image simulation to calculate permeability and mercury drainage capillary pressure

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Appendix:

Figure 1. *KU's HeliScan micro-CT*

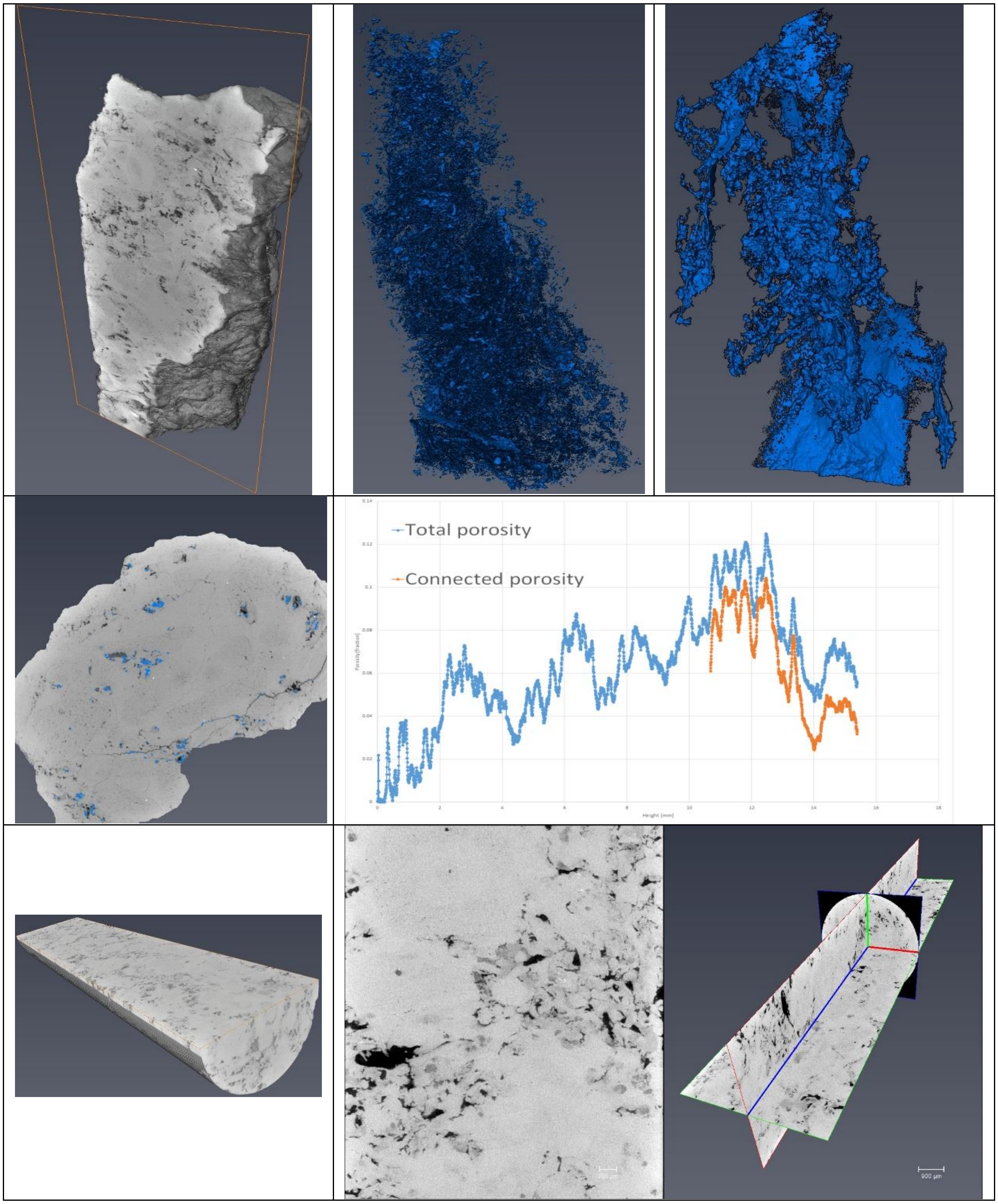

Figure 2. *Fairway Resources' reservoir with 3.8 & 2.8 µm resolution image highlighting the whole sample with clipping planes, pore space, connected pore space, micro-porosity regions, and porosity profiles*

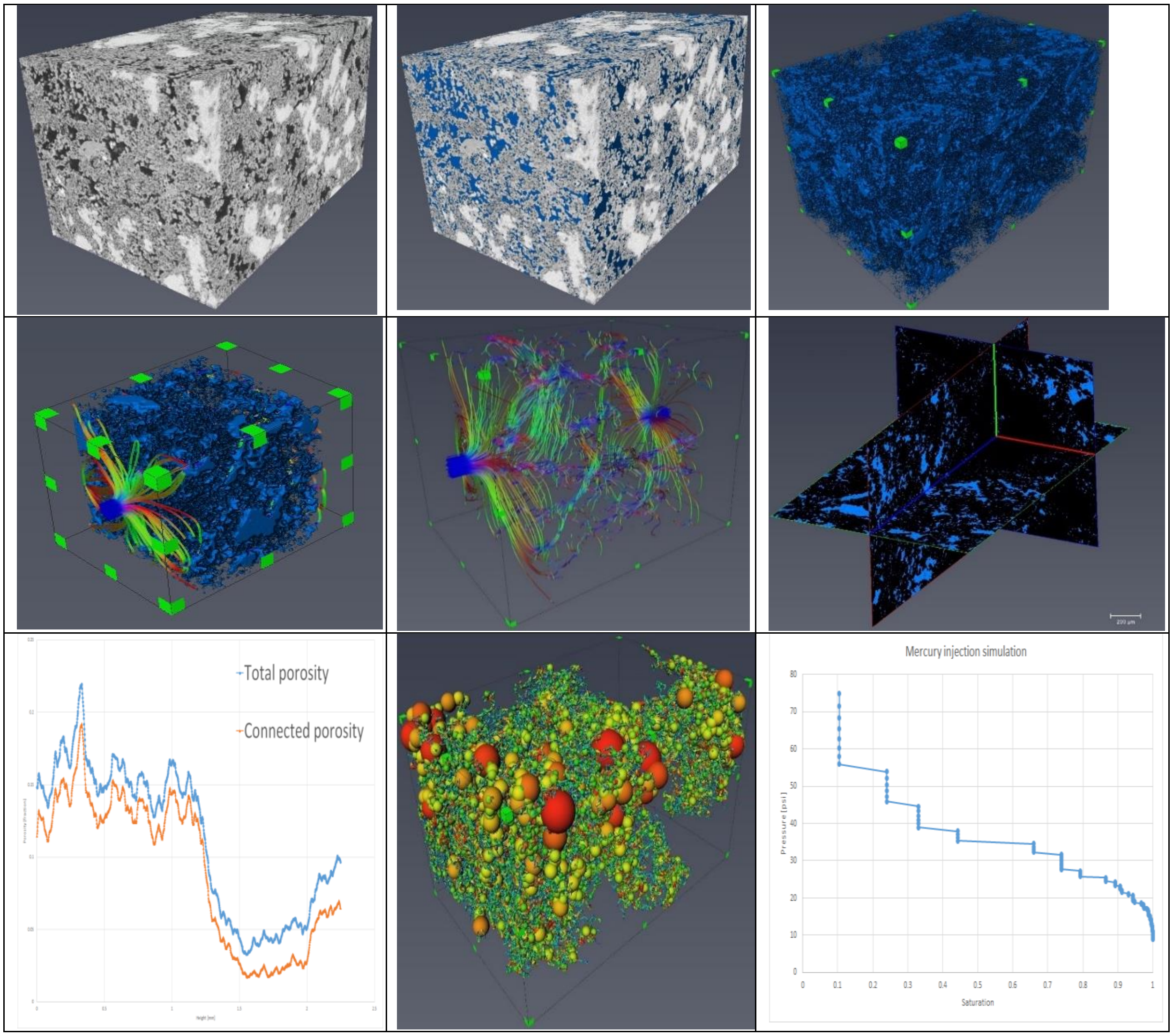

Figure 3. *Indiana limestone with 1.8 µm resolution image highlighting pore space, porosity profiles, representative pore networks, and mercury injection simulations*

Experimental Characterization of the Microporosity under Multiphase Flow Conditions Using a Micro-CT Scanner

Arsalan Zolfaghari, Amirmasoud Kalantari, Graduate student
Co-PI: Shahin Negahban, Robert Goldstein

SUBSURFACE APPLICATION: Carbonate and siliciclastic rocks (we are open to recommendations for selecting one of your representative carbonate samples. Please contact Dr. Robert Goldstein if you want your specific sample to be used in this project.)
STATUS: Proposed project
TIMING: To be completed in the future if recommended by membership, funded, or staffed
FUNDING: Seeking funding at this stage

Purpose

The purpose of this project is to conduct systematic series of two-phase oil/brine flow tests through a miniature carbonate core sample with a wide pore size distribution under a capillary-dominated flow regime. X-ray micro-computed tomography will be employed to generate a 3D pore-fluid occupancy map within the sample under different fractional flows during dual injection cycles of drainage and imbibition. Existence of a wide pore size distribution, which is a signature for many carbonate reservoirs, causes a fraction of the pore space to be unresolved (i.e., micro-porosity). Here in this project, we propose a differential imaging technique to distinguish micro-porous regions from macro-pores with intermittent phase occupancy. This technique has been used to distinguish intermittent phase (i.e., pores that were periodically occupied by either oil or brine during the image acquisition stage) in a Bentheimer sandstone sample [Gao et al., 2017]. In this project, we also propose to do advanced image analyses to provide information on the connectivity of micro-porous regions and their role in multi-phase petrophysical properties during the co-injection of the wetting and non-wetting phases. Specifically, we will focus on fluid/fluid displacements in pores adjacent to the drastically smaller pore spaces (i.e., micro-porous regions) to investigate their impact on displacement mechanisms at pore levels. We report *steady-state* saturation profiles along the core length and subsequently, look for the pore space topological features that impact the evolution of such saturation profiles. We measure the main petrophysical properties of the sample namely porosity, permeability, oil/brine relative permeability, and capillary pressure curves during both drainage and imbibition flow cycles. KU's miniature core-flooding system integrated with a HeliScan micro-CT imaging system will be used.

Project Description

We propose to use digital core analyses to investigate the impact of microporosity on multiphase flow in a carbonate sample. This is done by obtaining high-quality pore-level images of the fluid/fluid and fluid/rock interactions in the vicinity of microporous regions using a HeliScan micro-CT at the University of Kansas [Zolfaghari and Negahban, 2020]. This scanner has been integrated with a dedicated multi-phase core-flooding apparatus consisting of high-pressure pumps, transducers, and core holders. The core-flooding apparatus has been designed to enable in-situ injection of multiphase fluid flow, i.e., inside of the imaging chamber of the micro-CT. The sample will be mounted within the HeliScan micro-CT's chamber for the entire course of a flow experiment. There will be no need to move the core holder from the micro-CT chamber. Performing experiments in-situ, we collect reference and target state scans to produce unsurpassed images of the multiphase flow displacements in porous media. Obtaining reference and target scans, we will investigate fluid/fluid and fluid/solid interactions at pore levels by primarily focusing on pores in close proximities of microporous regions. The results of this project would impact our attempts to estimate reserves in formations that have wide pore size distributions, and subsequently, their potential waterflood recovery factors.

In a water-wet sample, we speculate micro-porous regions to have nonnegligible brine saturations at the end of oil injection. Image resolution impacts these microporosity saturation profiles since it determines the maximum pore sizes that can not be resolved. Therefore, the saturation of these micro-porous regions (e.g., at the end of drainage) depends upon image resolution. Regardless of the resolution, these unresolved micro-porous regions contain brine, providing additional pathways for electrons to decrease the sample's resistivity. This causes the problem of "Low Resistivity Pay" zones where reserves are underestimated (based on Archie's equation) for formations with wide pore size distributions. During imbibition (i.e., brine injection) however, we hypothesize a higher *initial* oil recovery factor for the microporous regions. This is because in a water-wet sample water prefers to displace oil from smaller pores as they have higher oil/water threshold capillary pressure (i.e., lower water entry pressure) [Zolfaghari and Piri, 2017 a, b]. These microporous regions could provide pathways for the brine to bypass oil globules in the larger neighboring pores. This phenomenon could potentially decrease oil recovery factors during waterflooding.

To bypass oil globules in the larger pores, the brine would overcome two different types of forces at the pore level: viscous forces in the microporous regions and capillary forces of the water-to-oil displacements in the intermediate-size neighboring pores [Zolfaghari and Piri, 2017 b]. Pore space topology, connectivity, and conductivity of the microporous regions dictate whether these *water-microporous-oil* displacements could happen far away from the displacement front. It depends on whether microporous regions could conduct *enough* volume of the brine phase to trigger either piston-like, snap-off, or pore-body filling during an imbibition process. We emphasize again that water-to-oil displacements, far away from the displacement front, would significantly decrease waterflood recovery factor as it facilitates bypassing of oil in the large pores.

This project is well aligned with the outline of other KICC prospectus projects focusing on the characterization of the microporosity regions. See KICC's prospectus projects entitled: "An Integrated Approach for a Closed-Loop Microporosity Characterization" and "Digital Rock Physics of KICC Carbonate Formations". The KICC offers a complete range of DRP services for characterizing microporosity by providing a platform to link the results of different projects. For instance, in this project, we propose to investigate a carbonate sample with a considerable amount of microporosity under multiphase flow conditions. The results can then be used directly in other KICC projects (e.g., CMAPS for pore-level simulation of microporosity as explained in another KICC's prospectus). Please see those prospectus projects for more details.

Deliverables

The main petrophysical properties of the sample under multiphase flow condition will be measured and reported. They include porosity, permeability, oil/brine relative permeability, and capillary pressure curves during drainage and imbibition. Moreover, *steady-state* saturation profiles along the core will be reported. We will specifically look for the pore space topological features that result such saturation profiles to evolve. We collect 3D tomograms of the sample during each flow experiments. All 3D images and analyses will be available to members. Any new findings with regards to the impact of microporosity on pore fluid occupancies will be documented and shared with members.

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***Figure 1**. The University of Kansas's HeliScan micro-CT scanner and its integrated flow system*

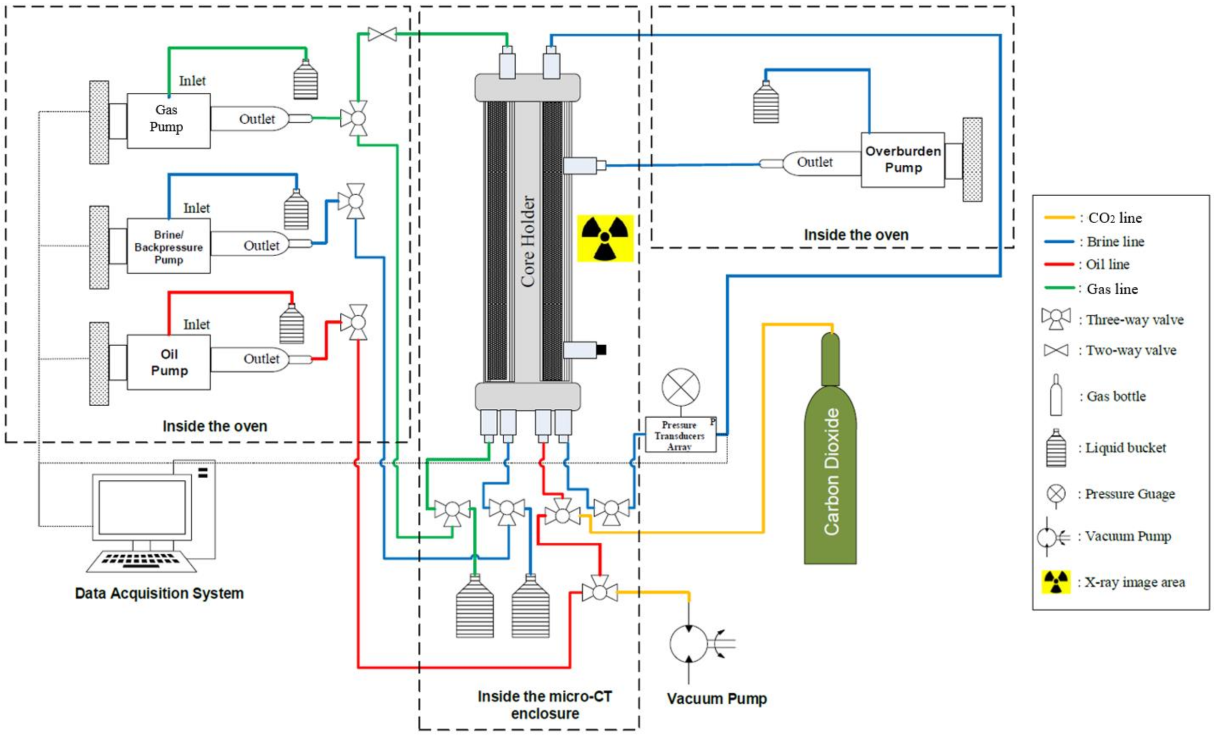


Figure 2. *Schematic diagram of the high-pressure miniature core-flooding system at the University of Kansas*

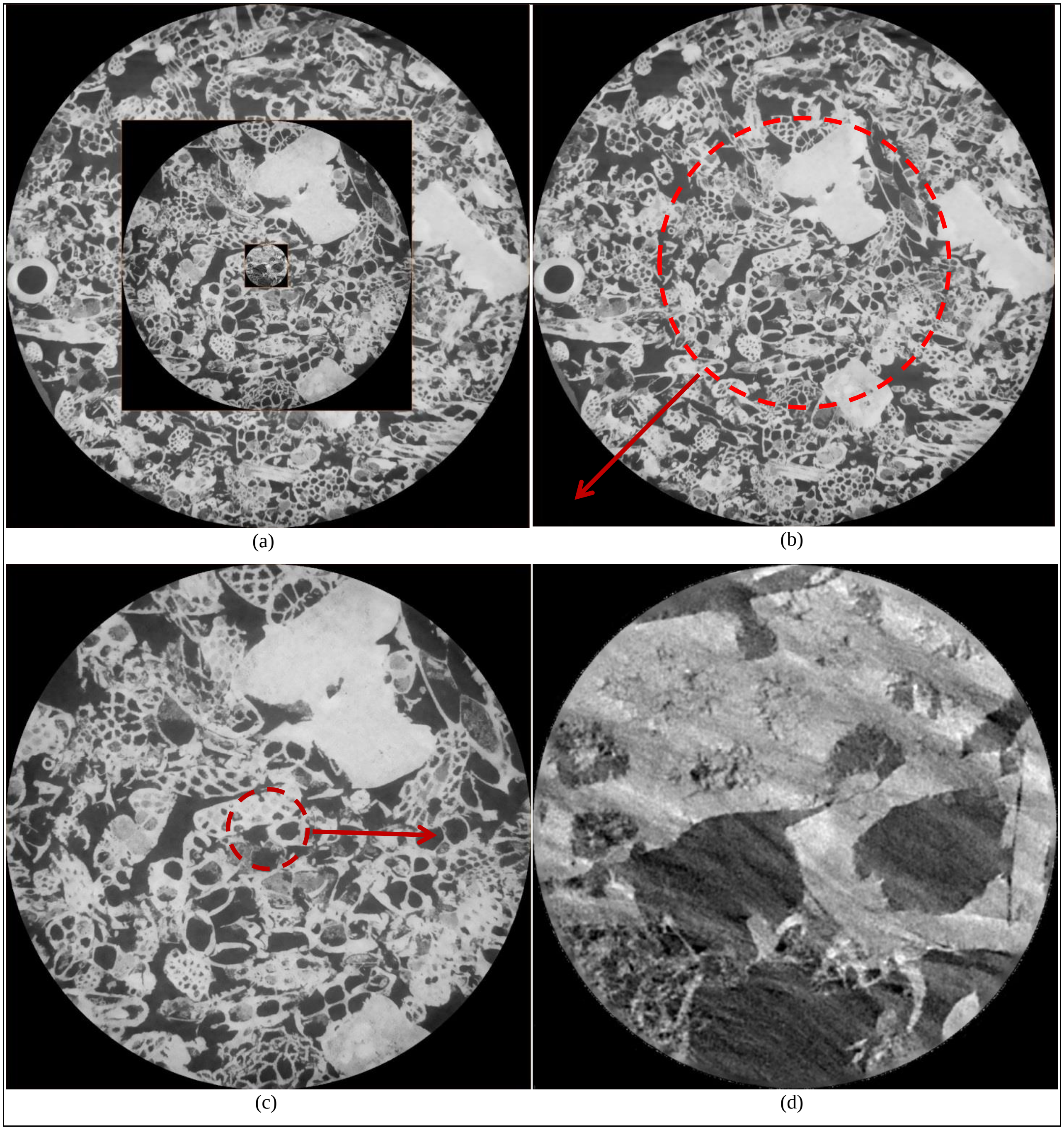
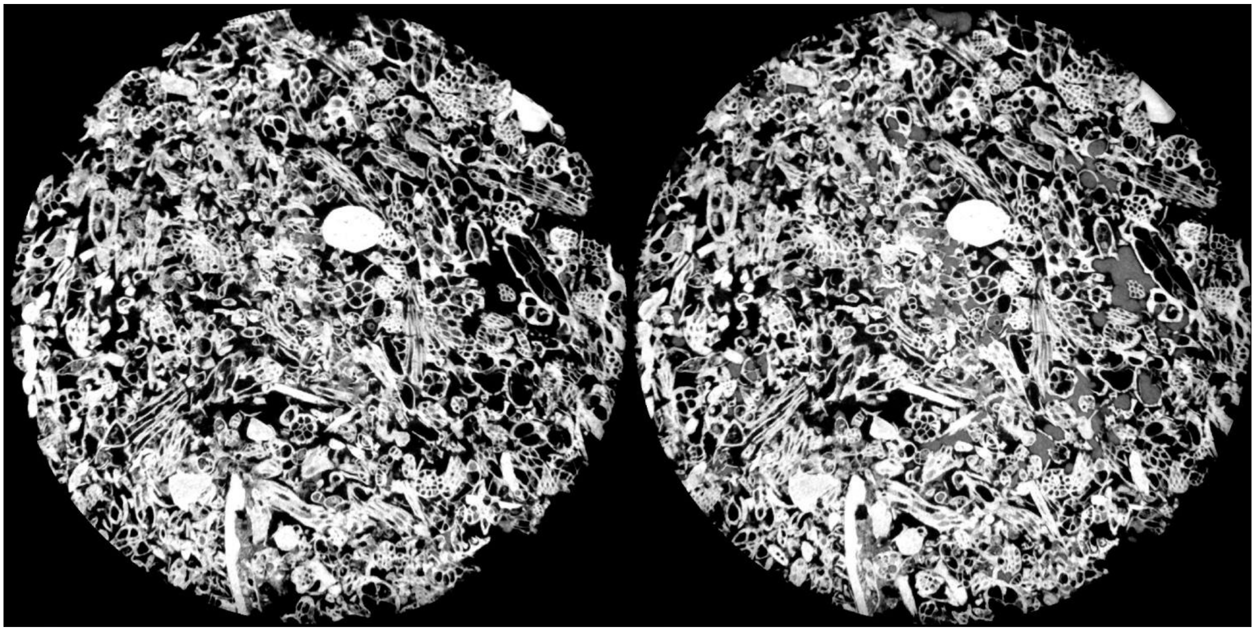
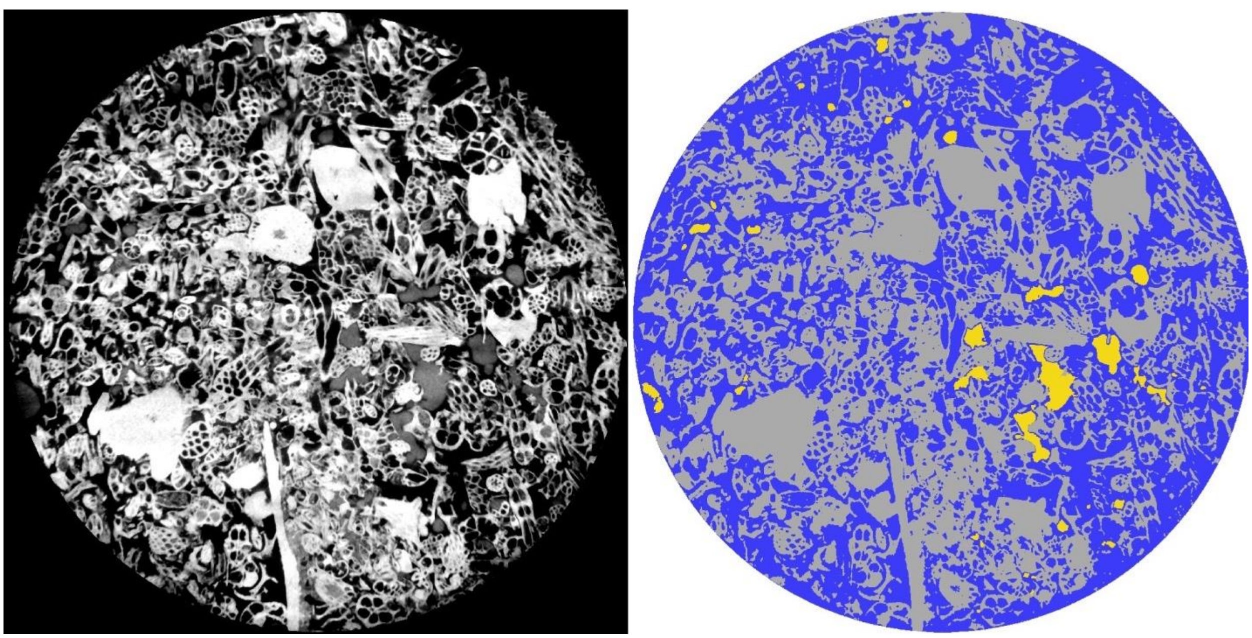


Figure 3. *The impact of resolution on the porosity values based on images in Gambier limestone sample: (a) the overlap of three micro-CT images with different resolutions, (b) the lowest resolution of 4.52 µm with 8.83-mm diameter, (c) the intermediate resolution of 2.51 µm with 4.9-mm diameter, and (d) the highest resolution of 0.764 µm with 0.73-mm diameter [Ref. unpublished work of PI].*



(a) (b)

Figure 4. *The X-Y cross-sectional images (perpendicular to the flow direction) for the reference state (a), and the registered target state after oil breakthrough (b) [Ref. unpublished work of PI].*



(a) (b)

Figure 5. *A target micro-CT image (a) and its corresponding segmented image showing solid (gray), brine (blue), and oil (yellow) (b) after oil breakthrough [Ref. unpublished work of PI].*

Petrophysics of Oolitic Grainstones and Their Evolution

Hamilton Goodner, Gene Rankey, Chi Zhang, and Lynn Watney

SUBSURFACE APPLICATION: Data and concepts will be applicable to understanding petrophysical attributes of carbonate pores in oolitic grainstone reservoirs, including Jurassic and Cretaceous of the Middle East, and Pennsylvanian and Permian of the Midcontinent and Permian Basin.
STATUS: Focused-term project recently completed
TIMING: Thesis completed
FUNDING: Fully funded

Purposes

Reservoir characterization of carbonate strata can prove challenging due to inherent complexities in pore networks stemming from variable depositional fabrics and subsequent diagenetic modifications. Although general trends in porosity-permeability (phi-k) relationships within carbonates are well documented, how marked scatter in phi-k relates to specific properties of depositional fabric is less well constrained. To better understand this rock-pore relationship, this project examines carbonate grainstones across a range of diagenetic scenarios to test the linked hypotheses that ***1) distinct depositional fabrics exhibit unique pore attributes;*** and **2*) these distinct pore attributes define discrete trends in the relations between porosity and permeability*.** To address these hypotheses, observations of sediment and rock attributes will be integrated with phi-k and quantitative pore attribute data captured by nuclear magnetic resonance and digital image analysis. Refined understanding of relationships among carbonate depositional fabrics, pore attributes, and petrophysical parameters serves to advance predictive understanding of reservoir quality.

Project Description

Upon deposition, carbonate sediment is inherently complex, and includes a diverse range of pore abundances, geometries, and types. Post-depositional diagenesis modifies this initial complexity (Figure 1), and, in extreme cases, pores and matrix can even be inverted. As a result of the diversity of initial and modified pore-throat sizes, pore-throat size distributions, and pore interconnectivity (Bliefnick and Kaldi,1996), the same rock type (e.g., an “ooid grainstone”) might have high porosity and high permeability (e.g, Figure 1A), high porosity and low permeability (e.g., Figure 1D), or low porosity and low permeability. These factors create uncertainty in geologic interpretation of log character, velocity-porosity links, phi-k relations, and ultimately, reservoir producibility.

Whereas the general processes that control pore evolution can be characterized and broadly understood, quantitative understanding of how these changes influence pore networks and reservoir characteristics are less well constrained. In this context, the goals of this study is to examine the ‘evolution’ of total porosity, pore size distribution, pore throat sizes, and pore types of several iconic carbonate sedimentary textures. The project will start with a “simple” system – ooid grainstone (Figure 1), and include samples with a range of diagenetic modification. Rather than focusing on one geographical study area, this project examines previously studied sediment and rocks from a range of geologic settings and diagenetic histories.

Project examined recent (Figure 1A), Holocene (Figure 1B), Pleistocene (Figure 1C), and Pennsylvanian (Figure 1D) aragonitic oolitic sediment, and calcitic oolitic deposits of Mississippian age (not shown). Each sample was characterized by integrating observations of pore characterization and genesis (thin section petrography, digital image analysis and SEM), petrophysics (phi/k), pore throat characteristics (mercury injection capillary pressure (MICP); e.g., Melas, 1992), and porosity, pore size distribution (Nuclear Magnetic Resonance (NMR) T_2 relaxation times; Westphal et al. 2005; Vincent et al., 2011). NMR measures the volume of hydrogenated fluid filled void space, and the distribution of relaxation time T_2 provides the information on relative sizes of pores and their populations. Therefore, many petrophysical properties of carbonate rocks including porosity, permeability, mobile and bound fluid are calculated.

Capturing and isolating parameters of depositional fabric allows rigorous, statistical evaluation of their influence on different pore attributes. Statistical comparison of pore attributes with petrophysical data, within the framework of depositional fabric, permits explicit testing of the hypotheses. We expect the NMR T_2 data (characterizing micro-, meso-, and macro-porosity) and the MICP data (pore-throat sizes) to define classes that are related to sedimentologic and diagenetic fabrics.

Deliverables

Reservoir characterization includes understanding and modeling the three-dimensional distribution of petrophysical parameters such as porosity and permeability (Lucia, 1999). The data and insights generated from this study will provide quantitative constraints on the nature of, and controls on, distinct porosity-permeability relations, input essential for generating accurate facies-based geologic models. Near-final results presented at the 2018 annual meeting illustrate that the four oolitic sample sets produce distinct T2 curves, showing variability in peak amplitude, width, and relaxation time, as well as variable presence and character of secondary peaks (e.g. Figure 2). The analysis documents how this variability relates to depositional fabrics, diagenesis, and pore attributes. Final results are in the thesis of Goodner on the KICC website, and will be in the subsequent publication.

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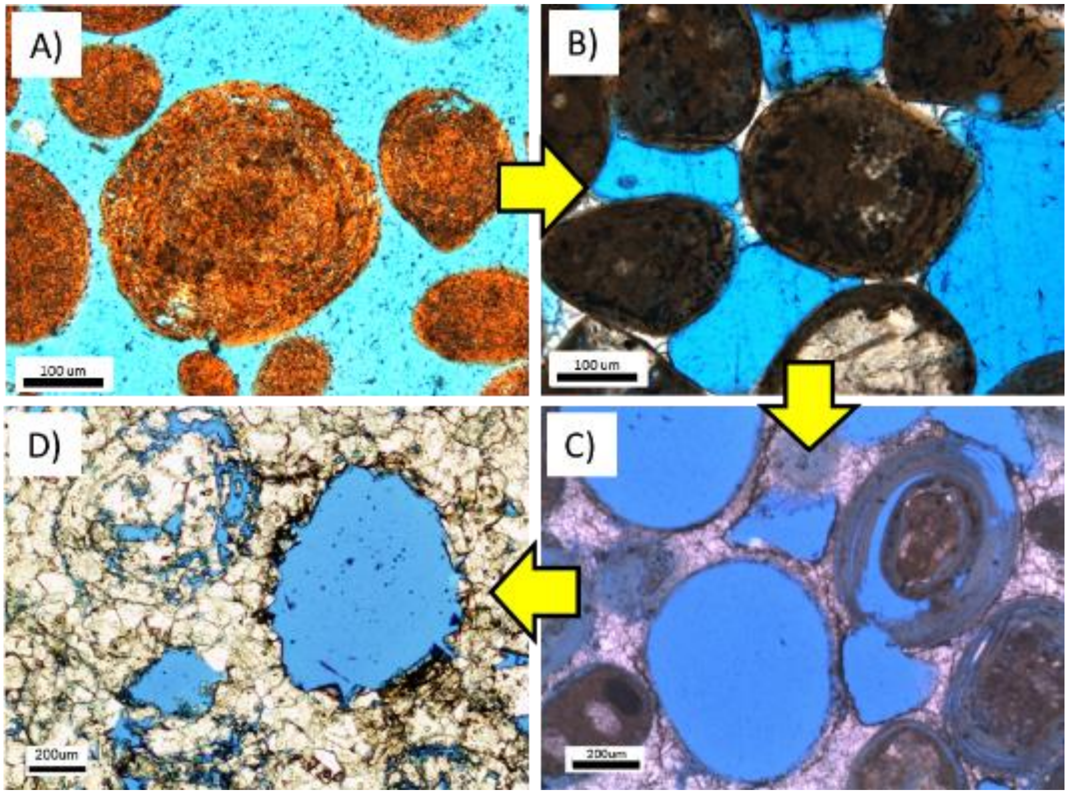

Figure 1. *Thin-section photomicrographs of several ooid grainstones. Note the pronounced changes in the abundance, size, and type of pores through the history of the rock from A) deposition, B) cementation, C) dissolution, and D) recrystallization. This study aims to characterize and understand the abundance, sizes, and distribution of pores as strata suffer through these alterations.*

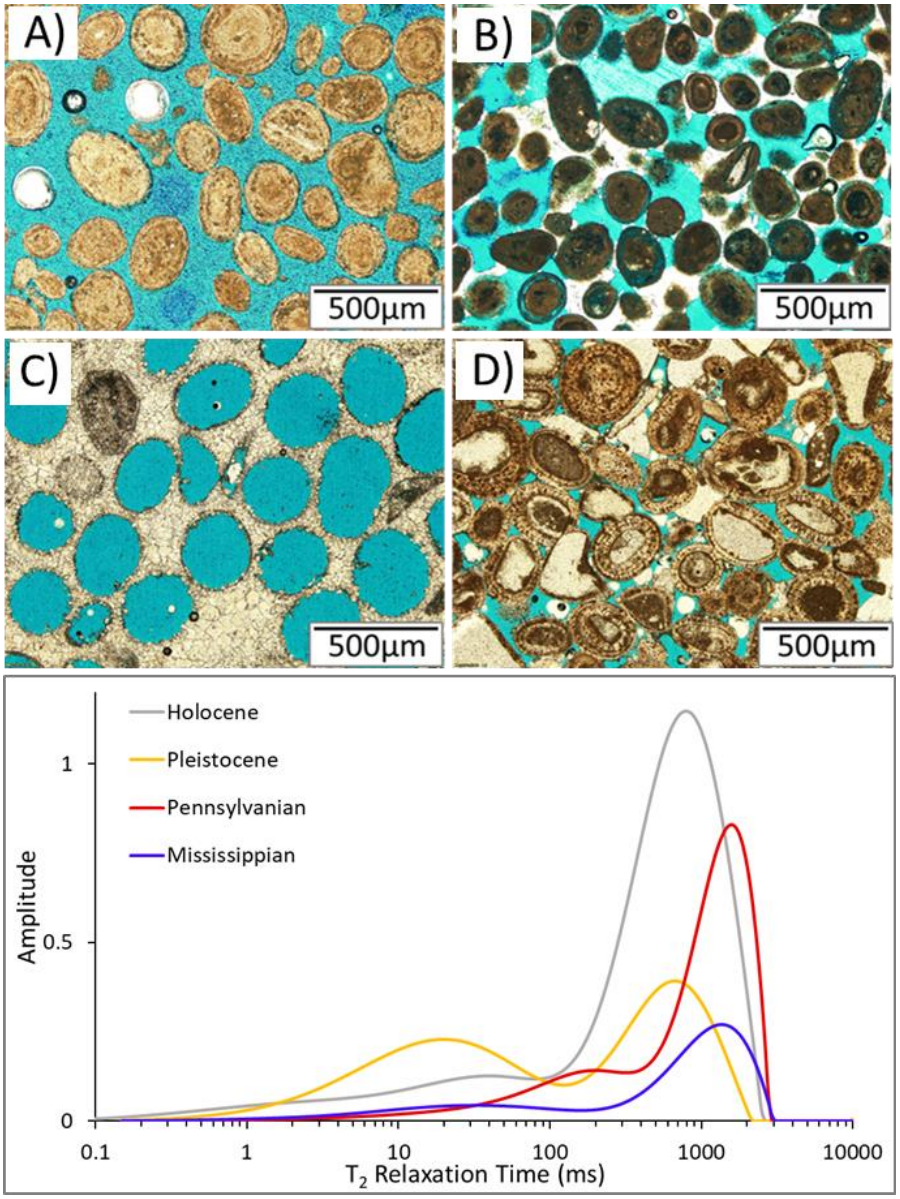

Figure 2. *Thin-section photomicrographs (A-D) and associated NMR T2 relaxation curves (E) of representative well-sorted medium sand oolitic samples of distinct ages (e.g., diagenetic scenarios). For each curve (E), relaxation time corresponds roughly to pore size, and amplitude represents frequency of a pore size, and total area under the curve corresponds to total porosity (%). A) Unconsolidated Holocene oolitic sand with dominantly interparticle porosity. This sample displays a high-amplitude, unimodal peak in the macroporosity domain (> 100 ms) (see Part E). B) Pleistocene grainstone. Note cementation of interparticle pores and partial dissolution of grains (bluish tint). Resultant pore-size distribution is more complex, exhibiting bimodal distribution with moderate amplitude macroporosity mode and clear contribution of microporosity (Part E). C) Pennsylvanian grainstone. Grains are dissolved and original pores are largely occluded with cement, leaving large isolated oomolds within a cement matrix. T2 curve (Part E) is dominantly unimodal with high amplitude modes at relaxation times greater than 400 ms. D) Mississippian grainstone. Note preserved ooids and small interparticle pores; corresponding T2 curve (Part E) displays low amplitude modes at relaxation times greater than 400 ms. E) NMR T2 relaxation curves for the samples in A-D.*

Integrated Geological and Petrophysical Expression of Oolitic Shoals

Gene Rankey, Chi Zhang, and John Doveton

SUBSURFACE APPLICATION: Developing predictive models for the geometry of oolitic reservoir bodies, their internal porosity and permeability characteristics, and their mechanical properties has relevance for oolitic reservoirs, including Pennsylvanian of the Midcontinent, USA, Jurassic of the Middle East and US Gulf Coast, Permian of West Texas, and others.
STATUS: Phase 1 of project completed, project expansion planned
TIMING: Phase 1 results reported at 2018 sponsors meeting; project continuing
FUNDING: DOE, KICC; seeking additional data sets for comparison

Objective and Relevance to Sponsors

Characterizations of Holocene oolitic carbonate systems commonly are held as analogs for ancient reservoirs, although subsurface analogs can be modified by various stages of diagenesis (Beach and Ginsburg, 1980; Halley and Evans, 1983; Hazard et al., 2017). These comparisons have a fundamental assumption - that the character and patterns of deposition influence ultimate subsurface reservoir properties (thickness, porosity, permeability, elastic properties).

At the 2018 KICC meeting, we presented results of sedimentologic-geomorphic characterization and petrophysical analysis of a Pennsylvanian oolitic unit (the Dewey Limestone), using a suite of logs including resistivity, NMR, borehole image, and acoustic (compressional, shear, Stoneley wave). To explore sedimentological-petrophysical relations further, this study will characterize and interpret ***the relations among reservoir geometry, sedimentology, stratigraphy, petrophysical (porosity, acoustic, and elastic) properties of subsurface and outcropping Pennsylvanian oolitic successions***. Preliminary results suggest that the depositional template may be carried through diagenesis, and retain an influence on variability in reservoir properties. Broadly comparable facies and petrophysical patterns among ooid shoals of a range of ages raise the possibility that these types of signals may represent persistent (e.g. predictable) themes.

Background

Upper Pennsylvanian (Missourian, Kansas City Group) strata of Kansas represent a classic succession of Pennsylvanian cyclothems that include regularly interbedded carbonates and siliciclastics and which can be correlated across broad areas. An idealized Missourian cyclothem includes (from base to top) a transgressive carbonate (“middle limestone”), a deep marine shale (“core shale”), a regressive carbonate (“upper limestone”) and a regressive shale (“outside shale”) (Heckel, 1977; Watney 1980). Although the cyclothems containing this general pattern can extend 100s of km across the state, the component lithofacies can include considerable lateral facies variability (e.g., Watney 1980; French and Watney, 1989).

Within the succession lies several productive subsurface reservoirs (Watney, 1984; French and Watney, 1989). These reservoirs generally occur in the upper, regressive carbonates of the cyclothems, and commonly are hosted in oolitic strata. The focus of Phase 1 of this study, the Dewey Limestone, is one such oolitic carbonate unit, although it is not a reservoir in Cutter Field, the focus of this study.

Geology-Petrophysics Links: One Example

The Cutter KGS-1 wellbore data, supplemented by cuttings, provides information on the sedimentology and facies architecture of the Dewey Limestone. Examination and integration of the X-tended Range Micro Imager (XRMI) and dip meter logs illustrate the considerable variability within the Dewey (reported at 2018 KICC Annual Meeting). In this wellbore, the image and dipmeter data suggest a gradual upward shallowing succession, from subtidal nodular muddy carbonate, to lower energy bioturbated grainstone, to large-scale cross-laminated oolitic grainstone (subtidal subaqueous dunes), to rippled ooid grainstone, with burrows (active and stabilized intertidal flat) at the top (Figure 1).

Within the field, the Dewey Limestone ranges from < 10 ft to more than 32 ft (< 3.0 to >10 m) thick; areas with thick accumulations include porosity of greater than 20% and form NW-SE trending highs, separated by thins of low porosity (<15%). An extensive suite of petrophysical logs in one well (KGS Cutter 1) illustrates the character of the strata. Resistivity image logs and dip meter data motivate a subdivision of the succession into distinct depositional packages. These units include differences in porosity, acoustic (compressional and shear) velocity, velocity anisotropy, elastic moduli, and apparent porosity exponents (m_a). The data are consistent with a conceptual model that the Dewey Limestone in the Cutter Field area represents a tidal ooid shoal consisting of several units. Petrophysically, these units are interpreted to include changes in porosity and pore type, and a general upward increase in anisotropy, pore connectivity, and permeability.

These data, together with more regional cross-sections and well info from nearby wells in Cutter Field, provided the basis for evaluating the geometry, continuity, and orientation of reservoir bodies of the Dewey Formation. Integrated with the porosity, pore characterization and elastic properties, the data illuminated the relations between depositional and diagenetic processes and petrophysical variability within this oolitic succession.

Deliverables and Next Steps

The next phase of research will test the broader applicability of the geomorphic, sedimentological, and petrophysical trends, within and among shoals. To do so, we will integrate other, plug- and thin section-scale observations and analyses (see other proposals in this prospectus), with larger-scale log, facies, and stratigraphic/geomorphic observations (e.g. Figure 2). Our plan is to start with another Pennsylvanian oolitic succession, but we anticipate expanding to a broader range of oolitic strata, pending access to data.

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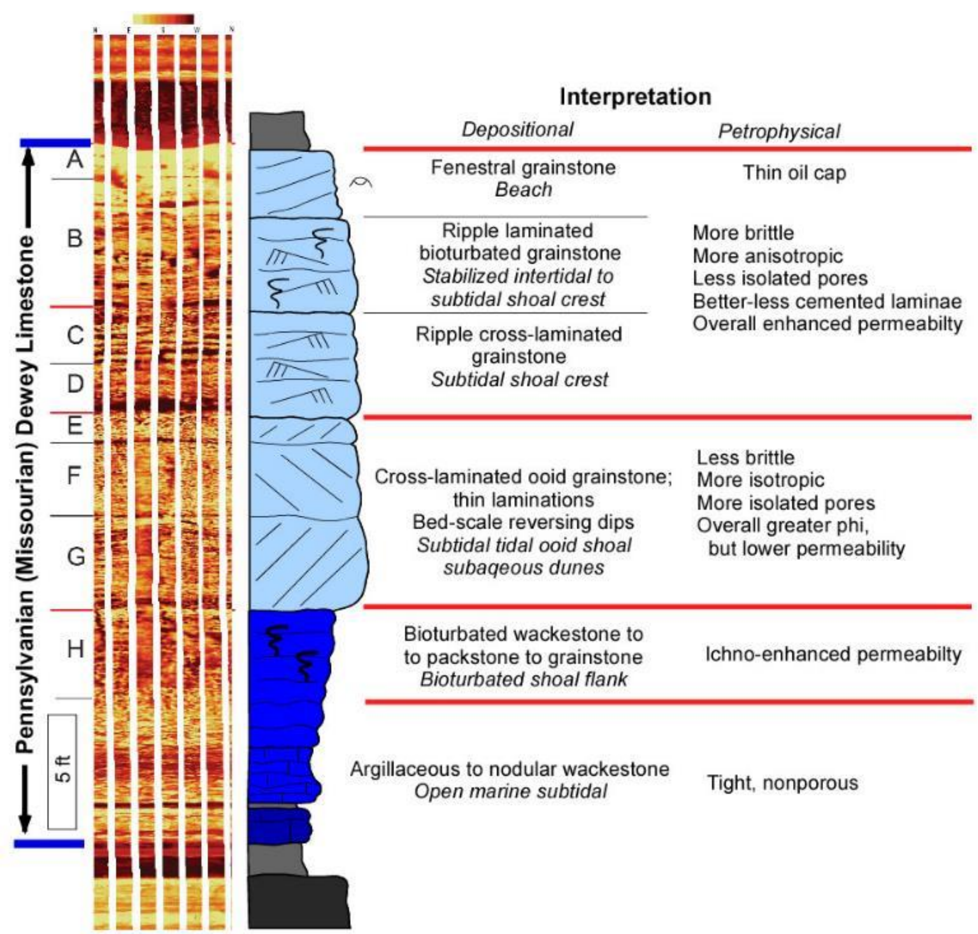

Figure 1. *Summary diagram of the integrated depositional and petrophysical interpretation of the Dewey Limestone. Each of these units also includes distinct petrophysical attributes. See Rankey et al. (2018) for details.*

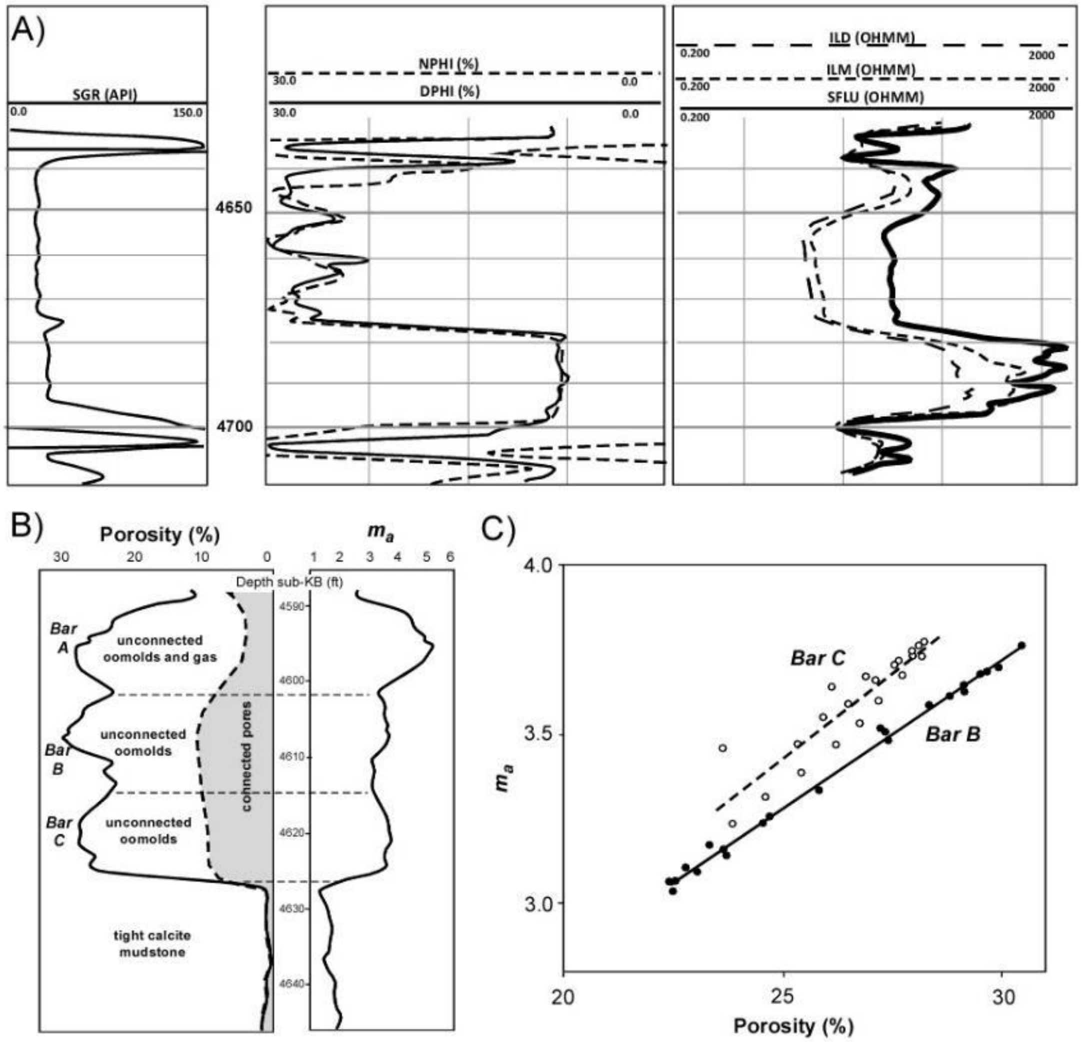

Figure 2. *Petrophysics of stacked oolite bars in a Pennsylvanian Bethany Falls limestone section in a gas development well in the Victory Field, Kansas (modified from Doveton, 2014). (A) Gamma ray, neutron-density, and resistivity logs; (B) Partition of porosity between electrically connected and unconnected pores (left) and computed porosity exponent, m_a (right); (C) crossplot of porosity exponent, m_a, against porosity in bars B and C, The upper bar (A) is excluded because of perturbing gas effects. Note the distinct character of each bar.*

The Oread Limestone: A Rosetta Stone for Carbonate Petrophysics and Seismic Stratigraphy

John H. Doveton, W. Lynn Watney, and Eugene C. Rankey

SUBSURFACE APPLICATION: Results will be most directly applicable to Pennsylvanian carbonate reservoirs, but the data and concepts will also be important for understanding the nature and geological controls on pore- to seismic-scale heterogeneity in complex carbonate reservoirs by integrating core, outcrop, log, and seismic data
STATUS: Continuation of multiyear project
TIMING: Ongoing
FUNDING: None

Purpose

Strengths of the KICC program provide broad coverage of outcrop and modern depositional environment studies. As industrial applications in geology are primarily engaged with the subsurface, this project proposes to leverage existing expertise on carbonate research to calibrate seismic character and modern log signatures to lithologic features. Logs that are run commonly today have a much expanded geological information content when contrasted with older logs that have been used ubiquitously (and often exclusively) for correlation; these advanced tools have not been systematically integrated with seismic characterization. It is timely to develop materials to promote a carbonate petrophysical education in industry and academia that is designed to closely coordinate outcrop and subsurface observation and analysis. At KU, the Oread Limestone is an obvious candidate as a teaching template (or "Rosetta Stone") for this purpose. The lithologically diverse Oread is recognized widely as an archtypal Pennsylvanian cyclothem, and has been investigated extensively over its eastern Kansas outcrop for more than a century. The Oread outcrops at KU, so that generations of geology students are familiar with its surface expression and interpretation, while its correlative equivalent occurs throughout the Kansas subsurface. It is readily accessible for training students and KICC sponsors about the calibrations among lithologic features, modern well-log signatures, and seismic character.

Project description

The Oread Limestone and Upper Carboniferous strata were logged with a comprehensive suite of tools in three recent wells in southern and southwestern Kansas along a lower shelf and shelf margin setting. Two multi-component 3D seismic surveys provide the basis for examination of carbonate petrophysical properties from pore to seismic scale.

Initial results were reported by Doveton et al. (2014) at a recent GSA meeting. The Oread Limestone was selected to serve as a "Rosetta Stone", where the "hieroglyphics" of subsurface logs and seismic signatures can be matched with the "Greek" of outcrop, drawn from student observation and their review of the extensive Oread literature. The "Oread experience" would then help to provide a bridge that seamlessly furthers knowledge gained in the KU geology curriculum to the practice of subsurface carbonate analysis in an industrial career.

The seismic, petrophysical, core, and outcrop data, combined with other well control and regional geological context, provide the opportunity to develop insights into the controls on petrophysical and seismic properties in relationship to oil and gas reservoir development. The Oread and Lower Shawnee Group in these wells and the 3D seismic reveal dramatic changes in internal properties and geometries of the Plattsmouth Limestone, and there are many interesting bedding sets that reflect cyclic variation over a wide range of scales, as well as intriguing sedimentological features in the Heebner black shale. Of particular geological and petrophysical interest are the spectral gamma-ray, neutron-induced capture gamma-ray elemental, resistivity imaging, nuclear magnetic resonance, and dipole sonic logs, in addition to more standard curves. These logs provide new, and detailed, perspectives on the character of the rock and pore systems, as calibrated by core and outcrop studies. Expanding in scale, the project will explore how depositional and petrophysical variability is expressed in the seismic data. Previous studies have illustrated that the seismic data capture a small Oread "shelf margin" that runs between the two wells. Integrating seismic modeling and seismic attributes with log and core data, this project will expand on this first-order finding to assess the geologic and petrophysical variability in this interval – from pore to pool.

Deliverables

A web-based learning module of integrated Oread outcrop, petrophysics, and geophysics designed to be a component of a broader carbonate petrophysics online training program. The project will explore the seismic expression of geological and petrophysical changes (facies, thickness, porosity, pore type), insights that may be useful for understanding analogous thin, stacked carbonate reservoir systems. Other deliverables can be suggested by consortium members.

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Carbonate-Rich Unconventional Reservoirs: Geobiology, Porosity, Sedimentology, Geochemistry, and Reservoir Controls

Fine-grained carbonates, both conventional and unconventional, represent one of the great future hydrocarbon resources upon which the industry will focus. These carbonates, typically known as chalks, marls, oil shales, and gas shales, are poorly understood in terms of their depositional processes, diagenesis, porosity, and permeability. Examples of some current and pending projects include:

Diagenetic Controls on Distribution and Reservoir Character of Deep-Water Deposits in the Wolfcamp Plays of the Midland Basin

Robert H. Goldstein, Erich Dezoeten, Pete Dillett

SUBSURFACE APPLICATION: Permian Basin slope and basin center plays such as Avalon, Wolfcamp, Bone Spring, Leonard, Wolfbone
STATUS: Ongoing research with one major project on the Wolfcamp, Midland Basin
TIMING: Currently active
FUNDING: KICC and KU

Purpose

This project proposes to study diagenetic controls on porosity reduction and preservation in Bone Spring, Wolfcamp or Wolfbone carbonates of the Midland basin (Figure 1). It addresses the fundamental question of porosity preservation in deepwater carbonates to provide models for distribution of deepwater conventional reservoirs, unconventional reservoirs and nonreservoir rocks. The result will be a conceptual model by which the distribution of reservoir porosity in deepwater carbonate plays can be predicted.

Project Description

It is well known that many deepwater carbonates are deposited with great amounts of inter and intraparticle porosity. Many of these carbonates preserve this porosity at depth or are subject to diagenetic processes of porosity enhancement, leading to good deepwater conventional carbonate reservoir properties. On the other hand, the porosity in many other deepwater carbonates have largely been occluded by cementation and pressure solution. These diagenetic processes are primary controls on the lateral interface between grainy deepwater conventional reservoirs, low-permeability unconventional reservoirs, and non-reservoir rock. Predictability requires an improved understanding of diagenetic processes affecting deepwater carbonates.

In the Permian of West Texas and New Mexico, deepwater conventional reservoir systems are well known (Saller et al., 1989a,b; Hobson et al., 1985; Mazzullo and Reid, 1987; Mazzullo, 1989; 1994; Griffin and Breyer, 1989; Leary and Feeley, 1991; Montgomery, 1996; Pacht et al., 1996; Mazzullo and Montgomery, 1997). Harris and Wiggins (1985) reported diagenetic differences between shelf and basinal strata, and Mazzullo and Harris (1991) documented multiple diagenetic phases affecting Bone Spring deposits. In low-permeability unconventional areas of the basin there is still evidence for a history of cementation and fluid flow (Poros et al. 2014). Yet, in the grainy carbonates of the Avalon Shale in the center of the Delaware basin (KICC study by Stolz, 2014), porosity and permeability have been eliminated by diagenetic processes, even in grainy sediment gravity flow deposits.

Our group has pioneered approaches to petrographic, geochemical and fluid inclusion analysis for understanding diagenetic and fluid flow history of unconventional carbonate reservoirs (e.g. Goldstein and Mitchell, 2013). We propose to study the diagenetic history of lateral and vertical transects in the Midland basin to develop an understanding of the

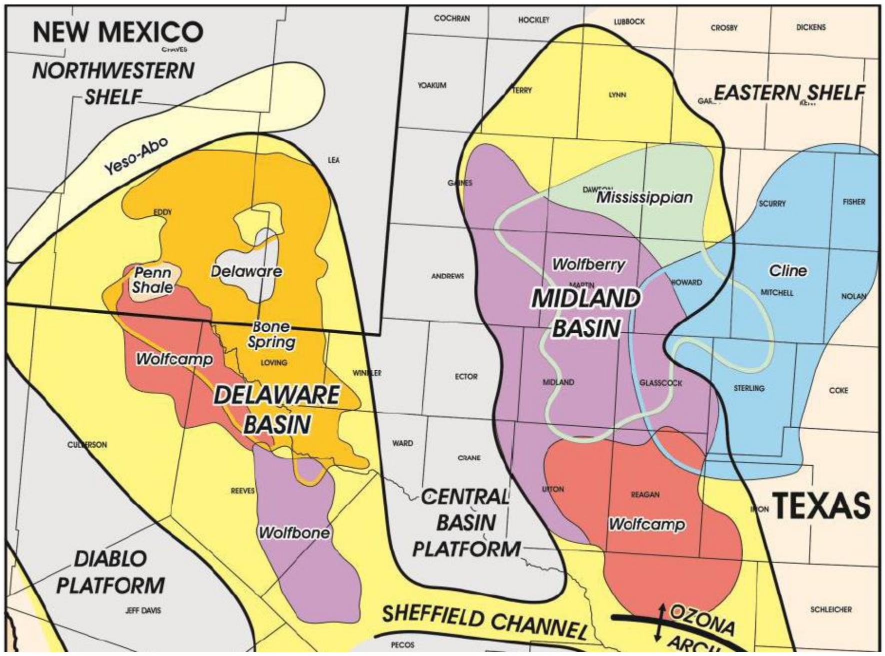

***Figure 1**. Location of current Permian Basin plays where diagenetic impacts on porosity are likely to be important.*

controls on porosity preservation. Methodology will include core description, thin section petrography, CL and UV petrography, SEM study, fluid inclusion microthermometry, and stable isotope analysis. These data will be used to understand the controls on porosity preservation and occlusion in Permian Basin deepwater carbonates (e.g. Mazzulo and Harris, 1991). The project will test multiple hypotheses of diagenetic alteration including:

- It is possible that cements are locally derived. For example, there is a negative correlation between clay and carbonate in the Avalon Shale. In thin sections, the carbonate in the muds have been attacked by pressure solution. If a grainy carbonate bed is surrounded by muds, much of the original depositional carbonate in the muds may have been dissolved. This may be because of the local chemical environment during burial induced by the clays and organic matter in the mudstone facies. The dissolved carbonate precipitates locally in the interbedded grainy carbonates where the local chemical environment is different. Where grainy carbonates are interbedded with muds or at least closely associated with them spatially, the carbonates are not porous. Where those muds are largely absent locally (such as in more proximal parts of the slope) there is no local source of dissolved $CaCO_3$ to cause cementation. Porosity in deepwater grainy carbonates are therefore preserved where the muds are absent or not abundant locally, immediately above or below, or interbedded with the grainy carbonate.

- Variation in cementation may be a secular change related to external forcing. It is well known that orbital forcing has an impact on early cementation of other deepwater carbonates (e.g. Molenaar and Zijlstrab, 1997). If carbonate cements are marine in origin and early, then rate of cementation may correlate to climate, sea level, or water circulation parameters.

- Porosity may simply be controlled by water depth. Given increased water depth, undersaturation with respect to carbonate phases is likely. Early grain-to-grain dissolution could be an early phenomenon related to pore seawater chemistry associated with depth and microbial metabolism. Similar grain-to-grain dissolution has been known for years in vadose settings as a mimic of grain-to-grain pressure solution. A similar process may take place in deepwater settings to reduce porosity early.

- Diagenetic history in the Midland basin deepwater carbonates is most likely complex and related to multiple events of fluid flow that had an impact on porosity evolution. This could include early marine diagenesis, later brine reflux, multiple events of fracturing and tectonically driven hydrothermal fluid flow, and then uplift and influx of meteoric waters (e.g. Hiemstra and Goldstein, 2014; Figure 2). Understanding the controls on fluid flow will provide improved models for cementation and thermal history.

Objectives of Wolfcamp Study in the Midland Basin

1. Establish a paragenetic sequence for mineral precipitation and dissolution, fluid migration, stylolitization, and fracturing. Initial results illustrate a complex record of diagenetic alteration and hydrocarbon migration (Figure 3).
2. Analyze FMI and core for drilling induced and natural fracture densities.
3. Through fluid inclusion analysis determine fluid temperatures and compositions, and tie to hydrocarbon migration.
4. Analyze $\delta^{18}O$ and $\delta^{13}C$ to constrain fluid composition, temperature, and diagenetic environment of formation. Analyze Sr^{87}/Sr^{86} to determine flow pathways.
5. Relate paragenetic events to geologic history and distribution of reservoir quality.
6. Interpret the spatial extent and gradational interfaces to which these geologic events affected an area.
7. Compose model for predicting porosity evolution and reservoir quality. Integrate model with FMI and rock mechanics data to hypothesize about geographic locations in the study area where reservoir-quality carbonates are more likely to exist.

Deliverables

The project overall will provide vertical and lateral transects of diagenetic history in deepwater deposits in the Midland Basin. These transects will be correlated to reservoir quality. Data will include paragenetic history, thermal signature from fluid inclusions, salinity history, hydrocarbon migration, and integration of paragenesis with fluid inclusions and stable isotopes. The result will formulate improved conceptual models for porosity preservation and cementation in deepwater carbonates in the system, allowing for improved predictability. It will predict the lateral interface between grainy deepwater conventional reservoirs, low-permeability unconventional reservoirs, and non-reservoir rock.

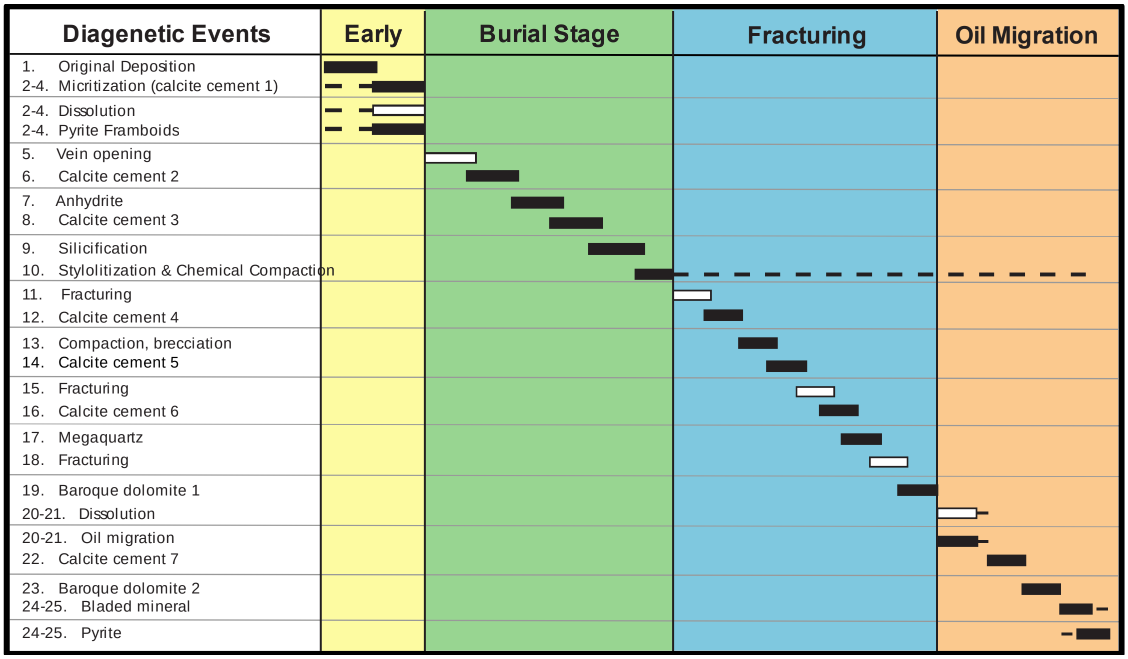

Figure 2*. Summary of paragenesis in Wolfcamp A in Howard County.*

Expected results for the Wolfcamp project in the Midland basin are that this diagenetic study will test Mazzullo's (1994) hypothesis that porosity is produced in close spatial association with organic-rich shales that developed acidic fluids during thermal maturation, as well as additional hypotheses. Mazzullo (1994) found that one of the four cores (the Indian wells core) in his study did not display the mesogenetic dissolution that is so significant in the other three wells even though the rocks are "mud-dominated" and the shales are thermally mature. This incongruity suggests that fluids charged with organic acids may not be the driver of dissolution and instead some other mechanism or more complex processes control major mesogenetic dissolution event. The new data should constrain fluid migration and a paragenetic sequence that can be tied to the geologic history of the region. We expect variation in the extant porosity in carbonate units to be spatially controlled by sources and migration pathways of fluids, some of which may be hydrothermal. Further, we expect lower porosity with proximity to shales or mud-poor facies, due to enhanced pressure solution and pore compaction caused by expulsion of acidic fluids from hydrocarbon source rocks. Additionally, we expect lower porosity with proximity to zones of high fracture density due to fractures serving as conduits for supersaturated fluids that precipitate cement.

Preliminary findings show that:

- Tectonic fracturing opened the diagenetic system and triggered injection of exceptionally hot fluids into the Wolfcamp A
- These hot fluids may have enhanced source rock maturation & may be a key reason for the success of this play
- Other late dissolution, however, may have resulted in net porosity loss by enhancing chemical compaction

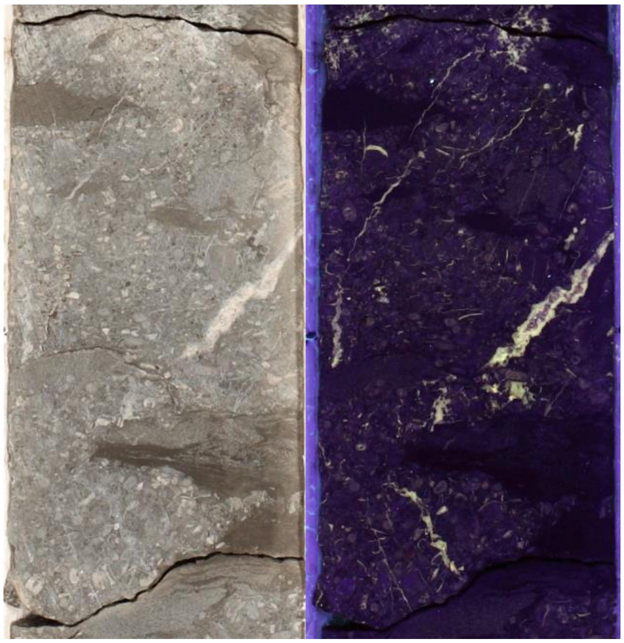

***Figure 3**. White light and UV photos of Wolfcamp A core from the Midland Basin. Preliminary results illustrate a complex history of diagenetic alteration and hydrocarbon migration.*

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Diagenetic Controls on Reservoir Character of the Wolfcamp and Bone Spring in the Delaware Basin, Texas

Robert H. Goldstein

SUBSURFACE APPLICATION: Wolfcamp, Wolfbone, Bone Spring, Avalon Shale, Delaware Basin Unconventionals
STATUS: Focused-term project in progress
TIMING: Began in 2018
FUNDING: Partial from KICC

Purpose

This is a diagenesis study on carbonate sediment gravity flow deposits and pelagic facies in a mixed carbonate and fine-grained siliciclastic system. Previous KU research on carbonates from the NW shelf, Val Verde basin, and eastern Midland basin show evidence of hydrothermal fluid flow that was triggered by Laramide tectonism. This overprinted the burial thermal signature, impacted porosity and hydrocarbon migration. Other studies of the Delaware basin center, however, have shown that the Wolfcamp and Bone Spring have three phases of fracturing and cementation, one of which shows dominance of *beef* calcite, which has been interpreted to result from overpressure in a closed system (Poros et al., 2014). This system can be regarded as a relatively closed end-member in terms of diagenetic system and porosity evolution, and can be compared to core in more highly and repeatedly fractured settings that show more open system diagenesis. The study will compare the two settings in the Delaware Basin (Figure 1) and develop a model for what reservoir properties to expect in the open system versus closed system end members. This will provide a hydrologic and structural model for prediction of reservoir properties so that geophysical techniques can be used to predict reservoir quality.

Project Description

Basinal unconventional plays have breathed new life into the Permian basin. This province is now one of the largest petroleum provinces in the world, and has proven a successful investment for both large and small oil and gas companies. Many of these reservoirs are carbonate-rich. Successful completions depend on: (1) understanding the sequence stratigraphic control on early cementation and its negative impact on reservoir properties (Figure 2); (2) localized controls on thermal maturity from hydrothermal fluid flow; (3) diagenetic controls on porosity; (4) fracturing history; and (5) either history of fluid migration or closed-system overpressuring. This project will be part of KICC's ongoing research to understand diagenetic controls on reservoir quality of unconventional carbonates.

Hypotheses:

1. Strata far from fault and fracture systems are largely closed systems and have diagenetic records of overpressure; in those strata, thermal history is predictable on the basis of burial history; given a closed system, locally generated acidic fluids generated during hydrocarbon generation enhanced porosity; alternatively other localized reactions occluded porosity

2. Strata close to fault and fracture systems were open systems and diagenetic records show fluid migration; in these systems hydrothermal fluids enhanced porosity and enhanced thermal maturity locally leading to modifications of reservoir quality
3. Nodular cementation is penecontemporaneous with deposition and has distribution that is predictable on the basis of the sequence stratigraphy already described by operators. It is hypothesized that nodular cementation is localized below surfaces that may be the downslope equivalents of maximum flooding surfaces.

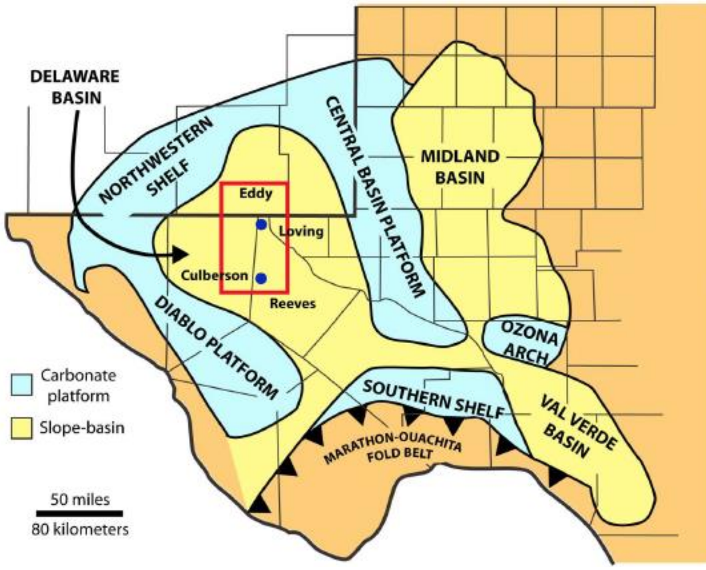

Figure 1. *Location of Delaware Basin*

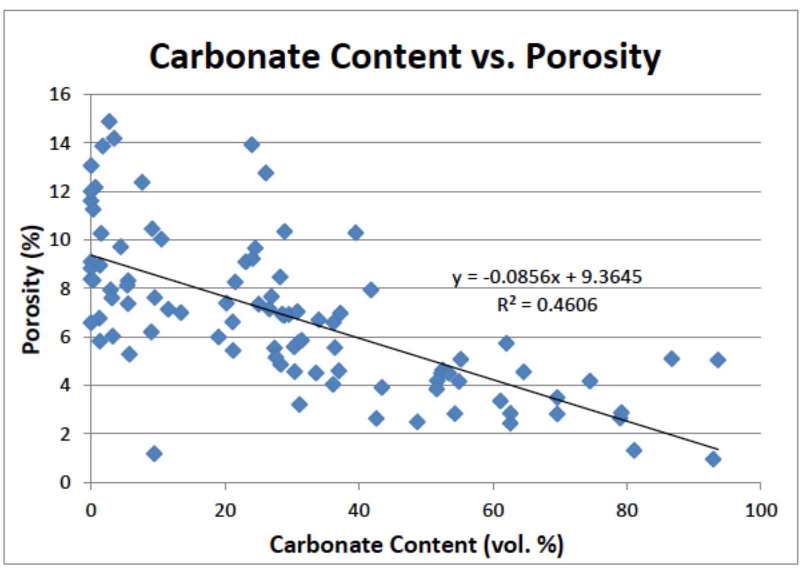

Figure 2. *Correlation between carbonate content and porosity in Avalon Shale. An example of early carbonate cementation leading to poor reservoir properties.*

Methods:

1. Sample core for diagenetic features to make thin and thick sections – sample core directly for whole-rock samples of nodular cementation for isotopic analysis

2. Paragenesis from thin-sections (includes CL microscopy)
3. Fluid inclusion analyses to determine temperature, salinity, and composition of the fluids that precipitated cement
4. Stable isotopes to understand diagenetic environment, and fluid temperature and evolution and to evaluate concretionary growth of calcite
5. Strontium isotopes to constrain origin and timing of fluids
6. U/Pb dating to determine timing of diagenetic events and to constrain burial history.

Deliverables and Expected Results

A Master's thesis will be available to KICC members.

1. Detailed diagenetic history the Wolfcamp and Bone Spring in fractured versus non fractured area
2. Geologic controls on the porosity distribution
3. Diagenetic conceptual model to aid prediction of reservoir quality in unconventional carbonates
4. Calibration of competing burial history models for the Delaware basin with thermal history data
5. Nodular cementation is expected to be early, but less predictable than the sequence stratigraphy because localized controls on sedimentation rate may overprint the primary sequence stratigraphic signature. This is a variant on models of nodular cementation in chalks.

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Depositional Controls on Distribution and Reservoir Character of Deep-Water Deposits in the Permian Wolfcamp, Bone Spring, and Wolfbone Plays of the Permian Basin

Evan K. Franseen, Robert H. Goldstein and John Doveton

SUBSURFACE APPLICATION: The proposed intervals of study form reservoir systems in the study area. Lessons learned can be applied to other similar deep-water systems
STATUS: Ongoing research; one project complete and another project to be completed in 2019. Results reported to sponsors
TIMING: 2-4 years upon funding
FUNDING: Seeking funding for additional projects

Purpose

Deep-water carbonates continue to show economic value as conventional and unconventional hydrocarbon reservoirs. Many of these reservoirs are derived from sediment gravity flows that redistributed shelf and slope material. These accumulations are complex, heterogeneous deposits, which must be understood for effective exploration and development.

This project explores sediment gravity flow stratigraphy, sedimentology, and reservoir quality within the Permian Wolfcamp, Bone Spring, and Wolfbone (co-mingled 3rd Bone Spring Sand and Wolfcamp) plays in the Permian basin of western Texas and New Mexico (Figures 1, 2) with the purpose of understanding what processes produce productive zones and areas within the plays. ***Using core, seismic, and petrophysical data, this project will investigate depositional processes in deep-water gravity-flow deposits as well as the reservoir potential in different settings. This study will allow enhanced prediction of productive zones and the heterogeneity within these deposits. Ultimately improved knowledge of the distribution and heterogeneity within these systems will provide predictive tools for better exploration and characterization of hydrocarbon-bearing deep-water deposits elsewhere.***

Project Description

Slope and basinal carbonates are complex, heterogeneous deposits that are poorly understood compared to both their shallow water and siliciclastic counterparts (Cook and Mullins, 1983; Playton et al., 2010). Playton and others (2010) provided an excellent summary of what is known about deep-water carbonates, noting that the variations and controlling factors in small-to-large scale architecture need further elucidation. Continued discovery of hydrocarbons within both conventional and unconventional deepwater carbonate reservoirs compels further evaluation of depositional processes and controls, facilitating better understanding and prediction of reservoir properties.

This proposed project is a continuation of our research on Permian basin unconventional plays. An initial study focused on the Avalon Shale and a second on the Wolfcamp "A" in

the Midland Basin (Flotron et al., in press). The Avalon study was completed in 2014 (Stolz, 2014) and the Wolfcamp "A" study will be completed in 2019. All results are available to consortium sponsors and indicate:
1) Sediment gravity flow deposits are dominant in the siliciclastics and carbonates in the Avalon and Wolfcamp "A". Grainy, carbonate-rich deposits form poor reservoir in the Avalon, whereas muddy, less carbonate-rich deposits form better unconventional reservoir (e.g. Figure 3). In the Wolfcamp "A", the muddy deposits have the best unconventional reservoir potential, and the carbonates have conventional reservoir potential.
2) Depositional trends changed throughout both Wolfcamp "A" and Avalon deposition as source direction and deposit types repeatedly changed. Sea-level changes and paleotopography were major controls on facies distribution and sweet spot location.
3) In the Avalon, carbonate-rich geobodies have been mapped and there are two phases of fan development, which occurred during regressions and lowstands, that are separated by a phase of apron development, which occurred during transgression and highstand. The thickest mudstones, deposited during transgressions and highstands, occur on the margins of fan lobes; these mudstones should be the focus of drilling (Figure 4). The most prospective areas have been mapped.
4) For the Wolfcamp "A", six regionally identifiable major units show progradational and compensational geometries, and each pair of major units has wedge-on-wedge relationships. The distribution of facies is controlled by topographic features in the slope. Overall, the stratigraphy is controlled by compensational geometries and relative sea-level fluctuations, with the coarse carbonates being dominant during relative sea-level highs and siliciclastics dominant during relative sea-level lows. The best unconventional reservoir sweet spots occur in muddy facies and are generally located in a medial location, between proximal carbonate deposits and carbonate deposits transported distally by compensation. The most promising potential sweet spots in carbonates enhanced by macroporosity are located proximally.

Similar to the Avalon Shale and Wolfcamp "A", Bone Spring and Wolfbone deep-water facies consist of organic-rich carbonate and siliciclastic deposits, much of which was transported into the basin. This proposed project will continue to examine deep-water sediment gravity flows (SGFs) to further understand their reservoir properties and their depositional and distributional controls. Hypotheses are aimed at answering several general questions:

1) What influences source, dispersal, and geobody configuration of SGF deposition (e.g. sea level, cyclicity, source of detritus)?
2) What controls the porosity and occurrence of the SGFs?
3) Are these deposits suitable reservoirs and how does geobody type and distribution affect reservoir potential?
4) Which rock properties lead to better reservoir?
5) How can controls on depositional system and rock properties lead to prediction of the best economics in each play?

Previous research projects on deep water deposits in the Delaware Basin have identified numerous examples of SGF deposits (Silver and Todd, 1969; Harris and Wiggins, 1985;

Hobson et al., 1985; Mazzullo and Reid, 1987; Saller et al., 1989; Leary and Feeley, 1991), which include thick debris flows, thin turbidites, and other grain-flow accumulations composed of shelf-derived debris. These include both conventional and unconventional reservoirs. Deposition occurs in sheet-like deposits (Hobson et al., 1985), channelized deposits (Silver and Todd, 1969; Harris and Wiggins, 1985; Loucks et al., 1985; Mazullo and Reid, 1987; 1989; Leary and Feeley, 1991), and complex channel-wedge systems (Mazzullo and Reid, 1987) that accumulated during both highstands (Silver and Todd, 1969; Saller et. al., 1989) and lowstands (Leary and Feeley, 1991). Many stratigraphic units are productive conventional reservoirs (i.e., Hobson, et al., 1985; Mazzullo and Reid, 1987; Saller et. al., 1989; Cook and Mullins, 1983) whereas other similar deposits are unconventional reservoirs or poor reservoirs. Despite the previous studies and ongoing studies, depositional details of the Avalon Shale, Wolfcamp, Bone Spring and Wolfbone are lacking and warrant further study.

Methods and Deliverables

1. *Determine rock properties and establish correlations to reservoir quality.* This goal involves measurement of TOC, porosity, permeability, mineralogy, and physical properties to evaluate fundamental controls on reservoir quality (e.g. Figure 3). Data will depend on partnership with sponsors and access to core data.
2. *Decipher the depositional processes of units within the Wolfcamp, Bone Spring or Wolfbone.* This goal involves core descriptions combined with stratigraphic data from objective three (below). The number and location of cores are dependent on access and availability from industry partners. Core description at a bed-by-bed scale will document the thickness, continuity, and contacts of units, the size, composition, and distribution of grains, along with sedimentary structures. Additionally, thin sections of SGF units will be analyzed to examine textures and origin of grains. The core is expected to contain grainy beds of sorted-to-unsorted shelf- or slope-derived debris (SGFs) interbedded with organic-rich, mudstone. The deposits will be evaluated for cyclic deposition throughout the succession associated with sea-level fluctuations or other controls.
3. *Determine the vertical and lateral stratigraphic architecture*. This objective defines the stratigraphic framework for this project and allows subdivision and description of the play. Where available, core data will be compared to geophysical log data to calibrate log signatures with subsurface lithology.
4. *Provide maps and geobody model for sweet spots in each play*. Geophysical logs and borehole data will be correlated to develop a stratigraphic model to map geobody type and distribution. The rock property data will be used to map the best economics in each play.

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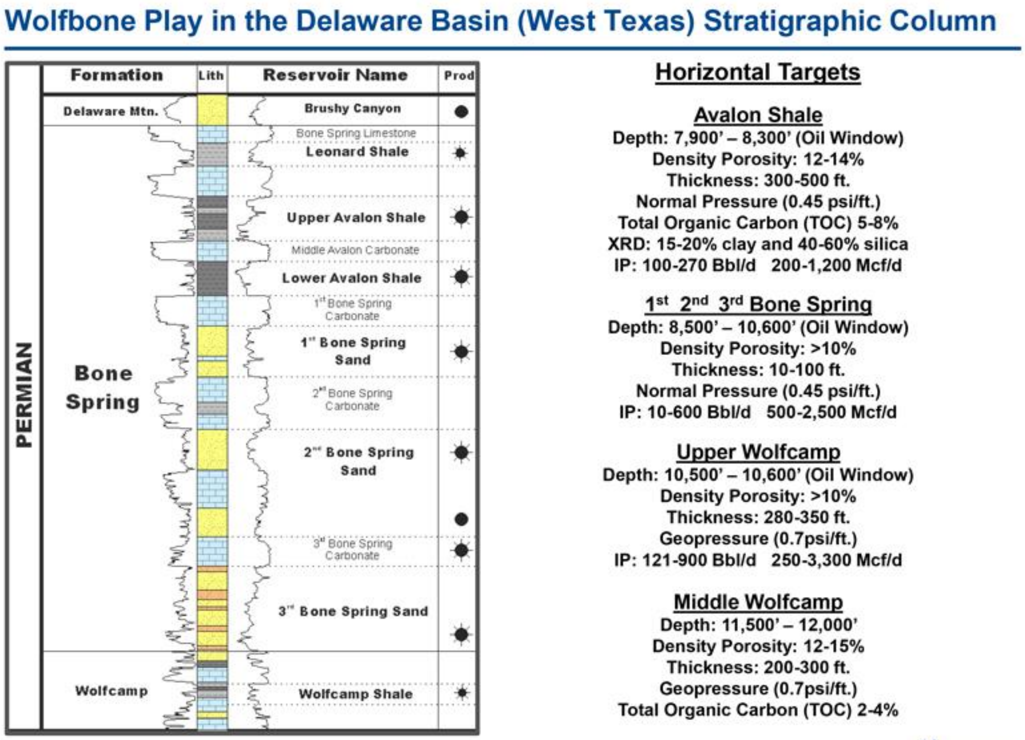

Figure 1. *Stratigraphic chart highlighting Bone Spring and Wolfcamp reservoirs in the Delaware Basin.*

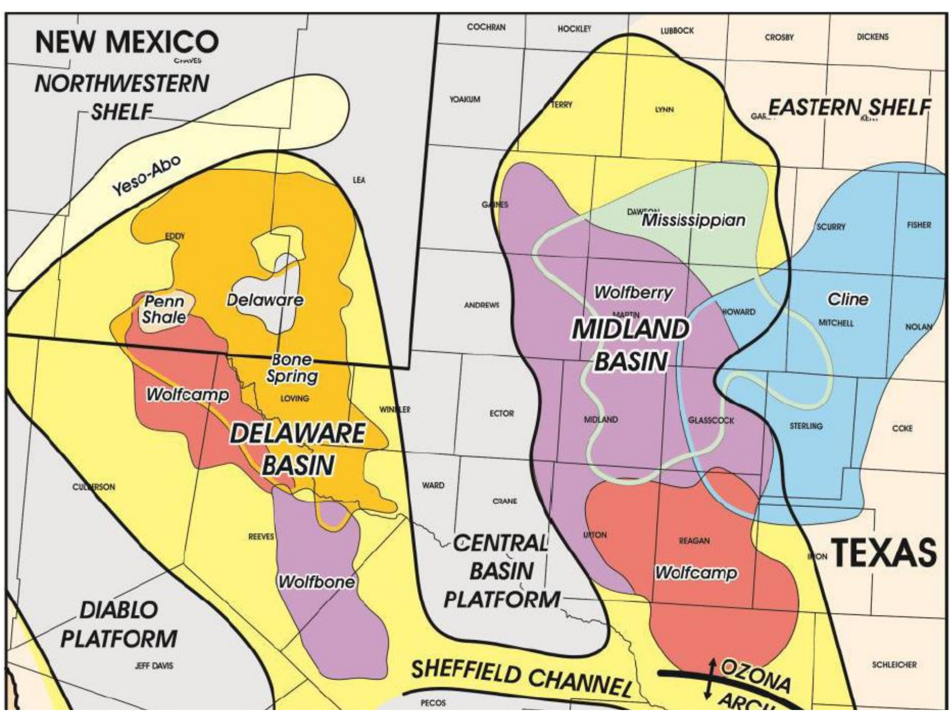

Figure 2. *Map showing trends of stratigraphic zones in the Delaware and Midland basins.*

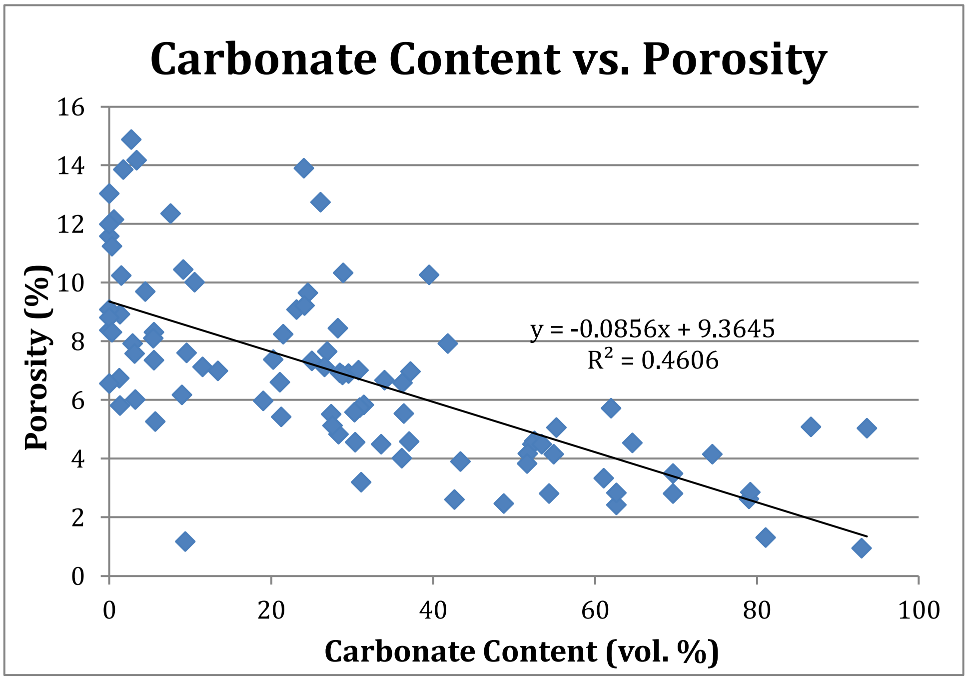

Figure 3. *Plot showing porosity in relation to carbonate content in the Avalon Shale. Porosity is shown to increase with decreased carbonate, illustrating the poorer reservoir properties of carbonate-rich strata.*

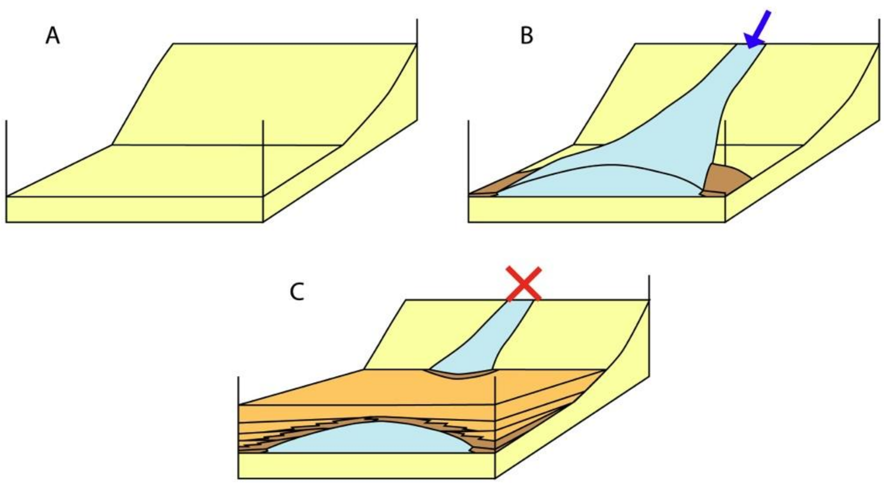

Figure 4. *Block diagrams showing the development of "sweet spots" in the Avalon Shale. A) shows toe-of-slope area decreasing in gradient out into basinal areas with no deposition. B) shows the development of large submarine fans (blue), sourced from the Northwestern Shelf, in toe-of-slope and basinal areas. C) Fan deposition has ceased and relief has been created that limits the lateral extent of SGFs sourced from other areas. Thus subsequent SGFs from other source areas are deposited on the margins and slopes of submarine fans lobes. This results in carbonate deposits from other source areas (orange) to be deposited on the lobe margins with better reservoir quality mudstones (brown) from distal SGFs deposited in slightly up-dip locations where flow is more restricted. Once the relief is filled carbonate SGFs can be deposited over areas previously restricted by fan lobe.*

Application of Raman Spectroscopy to Determine Thermal Maturity in Different Windows of the Eagle Ford Shale and the Impact of Gas Huff-n-Puff

Sherifa Cudjoe, Reza Barati, Jyun-Syung Tsau, Craig Marshall and Robert Goldstein

SUBSURFACE APPLICATION: Eagle Ford, Bakken, Wolfcamp, Utica, Marcellus, Woodford, Permian, Haynesville, Niobrara/Turner shale plays, and international tight unconventional plays such as Vaca Muerta in Argentina.
STATUS: Focused-term project in progress
TIMING: Significant results to be reported
FUNDING: Partially funded by Kansas Interdisciplinary Carbonate Consortium (KICC)

Purpose

The objectives of this work are: 1) to extract soluble bitumen from Eagle Ford samples from different windows (immature to gas window); 2) select features of interest with transmitted light and UV microscopy; 3) determine structural changes associated with maturity in insoluble organic matter (OM) with the Raman instrument; 4) correlate the Raman maturity-related changes to thermal maturity values from vitrinite reflectance (%R_o) in the different windows; and 5) investigate the effect of hydrocarbon gas huff-n-puff on selected OM states in oil windows.

Project Description

Vitrinite reflectance (*%*R_o) and T_{max} from Rock-Eval have their shortcomings in determining the thermal maturity of shales, one being dependent on identifying a certain maceral that is not always common in rocks of early Paleozoic age. The other being a bulk technique, and both becoming less reliable in the presence of free hydrocarbons like bitumen in shale samples or oil-based drilling mud contamination. The application of Raman spectroscopy as an analytical tool for structural characterization of carbonaceous/graphitic materials in addition to evaluating thermal maturity in organic-rich shales has gained widespread recognition over the years. Other researchers have used Raman spectroscopy for the evaluation of thermal maturity in organic-rich shales including [3, 4, 5, 6, 7]

None of these studies have been focused on the structural changes associated with OM in different windows having extracted the soluble component and correlated with maturity values, while considering the effect of gas huff-n-puff. Recent work on Lower Eagle Ford (LEF) shale samples in the oil window by Cudjoe et al [8] showed that the original maceral composition of the organic matter (kerogen) plays a significant role in the development of indicators of thermal maturity as opposed to the widely accepted notion of just temperature. Moreover, exposing the samples to gas injection revealed the displacement of the portion of what was characterized using SEM as the soluble OM. It will therefore be interesting to observe the effect of the gas on insoluble OM and how that translates to structural changes to be detected by Raman.

Bitumen Extraction: Eagle Ford samples from different windows will be subjected to bitumen extraction with organic solvents either through the soxhlet extraction [9] or ultrasonic extraction [10]; the ultrasonic extraction has a shorter experimental time and does not transform the OM. This is done to produce more reliable maturity measurements.

Microscopic Analysis & Raman Measurements: Transmitted light and UV microscopy will be used on double polished thin sections to select features of interest for Raman measurement. The Renishaw inVia Reflex spectrometer at the University of Kansas is employed at 514.5 nm emission to sample different regions within a feature and as many features as representative of maturity measurements via vitrinite reflectance.

Gas Huff-n-Puff: the samples will be placed in a huff-n-puff cell contained in an oven set at 125°C with hydrocarbon gas injection at a pressure of 3,500 psi and a soaking stage of three (3) days.

Deliverables
A definitive measure of maturity in the samples from Raman parameters is expected, which will be applicable to other shale plays. The effect of gas on insoluble OM in the absence of soluble OM will be better understood to help in the implementation of gas huff-n-puff in shale oil plays. Furthermore, an effective correlation between maturity-related Raman parameters will be developed, which will also be applicable to other shale plays.

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Regional Microporosity Distribution in Kansas Cherty Carbonate Reservoirs (e.g., Mississippi Lime)

Franek Hasiuk (Kansas Geological Survey)

SUBSURFACE APPLICATION: Basic research into spatial distribution of microporosity in a chert-rich carbonate play
STATUS: Awaiting funding
TIMING: Upon funding
FUNDING: Awaiting funding

Purpose

- To characterize the sizes of pores, pore throats, grains, and crystals within a microporous siliceous/dolomitic reservoir rock
- To document paragenesis of the microcrystalline rock textures that hosts micron-size pores

Project Description

Reservoir heterogeneity is one of the key factors complicating reservoir production that leads to inefficient reservoir recovery. The presence of microporosity in supergiant conventional carbonate reservoirs can account for upwards of 50% of total pore space in many large petroleum deposits. In smaller fields where hydrocarbon column height is insufficient to charge micropores, the phenomenon of "low resistivity pay" can occur from log response being dominated by brine-filled micropores. Rather than leave these reserves in the ground where well, surface facilities, and midstream infrastructure have already been developed in the reservoir, it is advantageous to develop new recovery strategies to effectively produce these pores. For engineers to design effective production techniques, they need to know the distribution of various pore types in the reservoir.

My long-term goal is to understand how microporosity and the rock matrix that hosts it forms and undergoes diagenesis. This project seeks to support this activity by mapping the regional distribution of microporosity in the Mississippi Lime in Kansas (Barber, Harper, Sumner, Reno counties, Figure 1) as part of mapping the relative abundance of the four Lucia pore types (interparticle, separate vugs, touching vugs, and microporosity, Lucia, 1995) within the play and correlating it to public production data. ***This will test the hypothesis that relative abundance of Lucia pore types is useful in predicting reservoir production behavior (Fullmer et al., 2014) and that these pore types can be mapped.*** The PI's work has already documented the variety of microcrystal types that occur in subsurface carbonate reservoirs (Kaczmarek et al., 2015) and used geochemistry to hypothesize on their origin and diagenetic pathways (Hasiuk et al., 2016).

We expect to find that hydrocarbon production rates are correlated to low pore system heterogeneity (e.g., when the pore system is dominated by one pore type) and that these areas of the play can be mapped due to their relation to diagenetic events within the play. This will allow operators to more accurately predict "sweet spots" for future exploration as well as develop more effective production technologies.

Deliverables

- Maps of pore system distribution
- Publications and presentations of research results
- Geochemical data
- Core analysis data (helium porosity/permeability, mercury pore throat size distributions)
- SEM images and FIB-SEM volumes of microcrystalline textures

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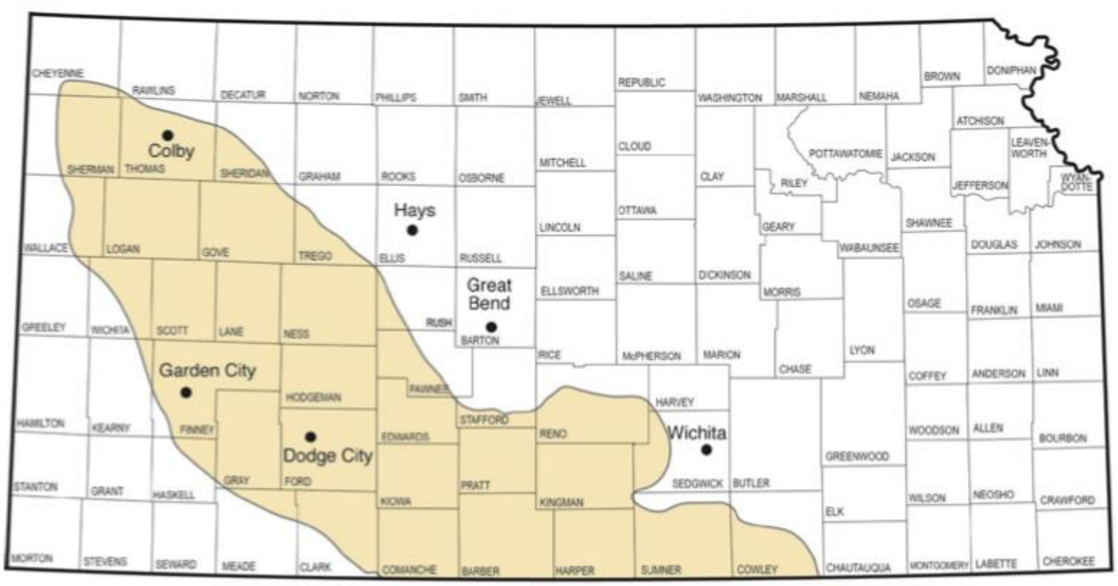

***Figure 1**. Map of Mississippi Lime play in Kansas (Evans and Newell, 2013).*

Stratigraphic Controls on Reservoir Character of Chert-Rich Distal Ramp Strata: Mississippian (Osagean) South-Central Kansas

Evan K. Franseen and Robert H. Goldstein

SUBSURFACE APPLICATION: The specific rocks of this proposed study are part of the Mississippian Lime reservoir system in the Midcontinent.
STATUS: Ongoing research; first project completed and results reported to sponsors
TIMING: 2 years
FUNDING: Seeking funding

Purpose

"Chat" is an informal name for high porosity, low resistivity chert reservoirs in the mid-continent (Watney et al., 2001) associated with ramp-margin Mississippian carbonate strata. The most productive and economic chat reservoirs are tripolitic chert exhibiting variable amounts of sponge-spicule molds, chert microporosity, vuggy porosity, and autoclastic breccia (Rogers et al., 1995; Montgomery et al., 1998). This study develops an understanding of the stratigraphic controls on ramp-margin lithofacies of lower Mississippian Osagean Series tripolitic chert, carbonate, and non-tripolitic chert facies in south-central Kansas. Stratigraphic controls related to sea-level changes are important, although regional structural setting plays a part. ***The effect of each of these variables on porosity distribution will be evaluated as a means of improving models for exploitation of reservoirs in ramp-margin settings.***

Project Description

Mississippian strata in Kansas (Figure 1) are cherty, partially dolomitized skeletal (especially crinoidal) packstone and grainstone and cherty, partially dolomitized and argillaceous wackestone and mudstone (Watney et al., 2001; Franseen, 2006). Osagean strata are siliceous sponge-dominated and heterozoan carbonate facies. These strata developed in inner ramp, distally steepened ramp margin, and slope settings. The Mississippian carbonates covered extensive areas of the central United States, and during the Osagean, the outer part of the ramp extended through southern Kansas (Lane and De Keyser, 1980). A deep seaway lay to the south (Scotese, 1999) and Kansas was located at approximately 20° south latitude (Witzke, 1990) allowing widespread carbonate accumulation. A lithofacies change, from north to south across a break in slope (Figure 2), is from clean mixed limestone and dolomite deposits to chert-dominated limestone and dolomite (Montgomery et al., 1998; Watney et al., 2001; Franseen, 2006; Watney et al., 2008).

Several hypotheses can be proposed for localization of chert reservoir facies. Chert may form in shallow water and replace shallow water facies. Chert may form in deep water and replace deepwater faceies. If tripolitic chert is deposited as sponge mounds, there should be geometries of constructional growth. If tripolitic chert is deposited in structural lows, there should be evidence of transport and fill. Mapping out tripolitic lithofacies using core descriptions and well logs will determine geometries and relation to structure/topography.

Controls on temporal and spatial distribution of facies will be analyzed using subsurface well logs, cores, and structural data. An internal sequence stratigraphic framework of ramp-margin to basinal chert-rich strata will be determined by integrating core descriptions and subsurface well logs.

Deliverables

The outcome of this study will provide a better understanding of depositional environment and distribution of ramp-margin lithofacies while determining how sea-level changes, and regional controls affect reservoir localization. A detailed north-south cross section will be used to illustrate geometries and determine sea-level effects on facies. The results of this study will contribute to a better prediction of enhanced reservoir porosity and delineating additional conventional and unconventional gas reservoirs in ramp margin systems.

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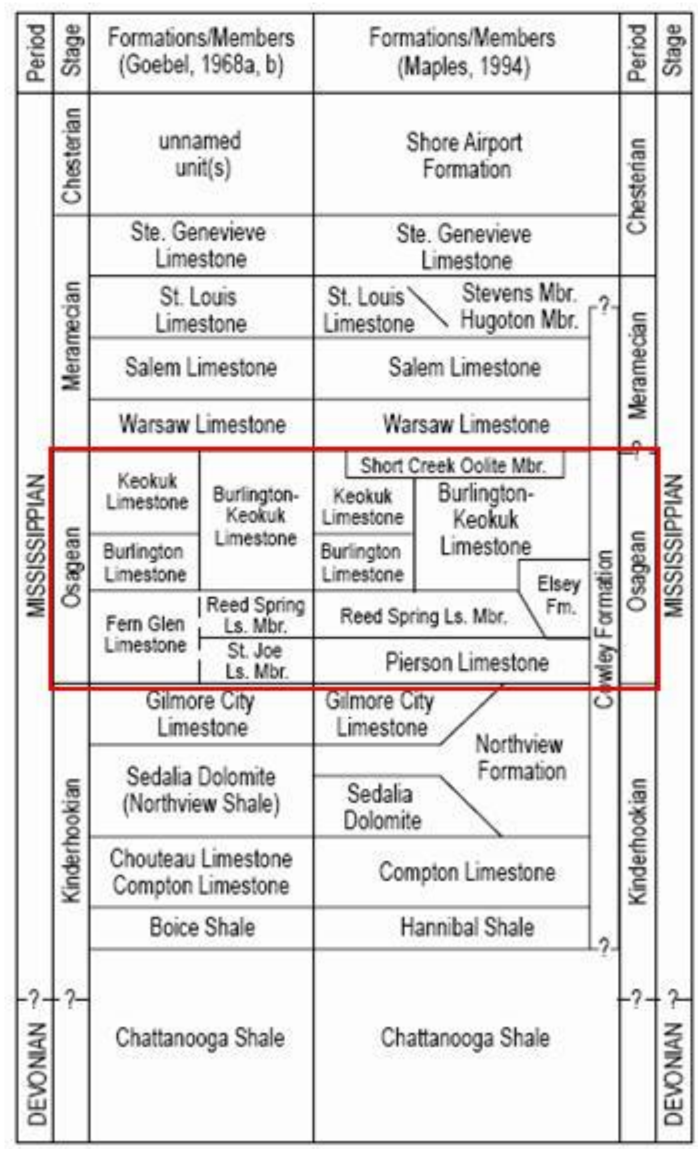

Figure 1. *Mississippian stratigraphic nomenclature used in Kansas (Watney et al., 2001). Red box indicates strata of interest.*

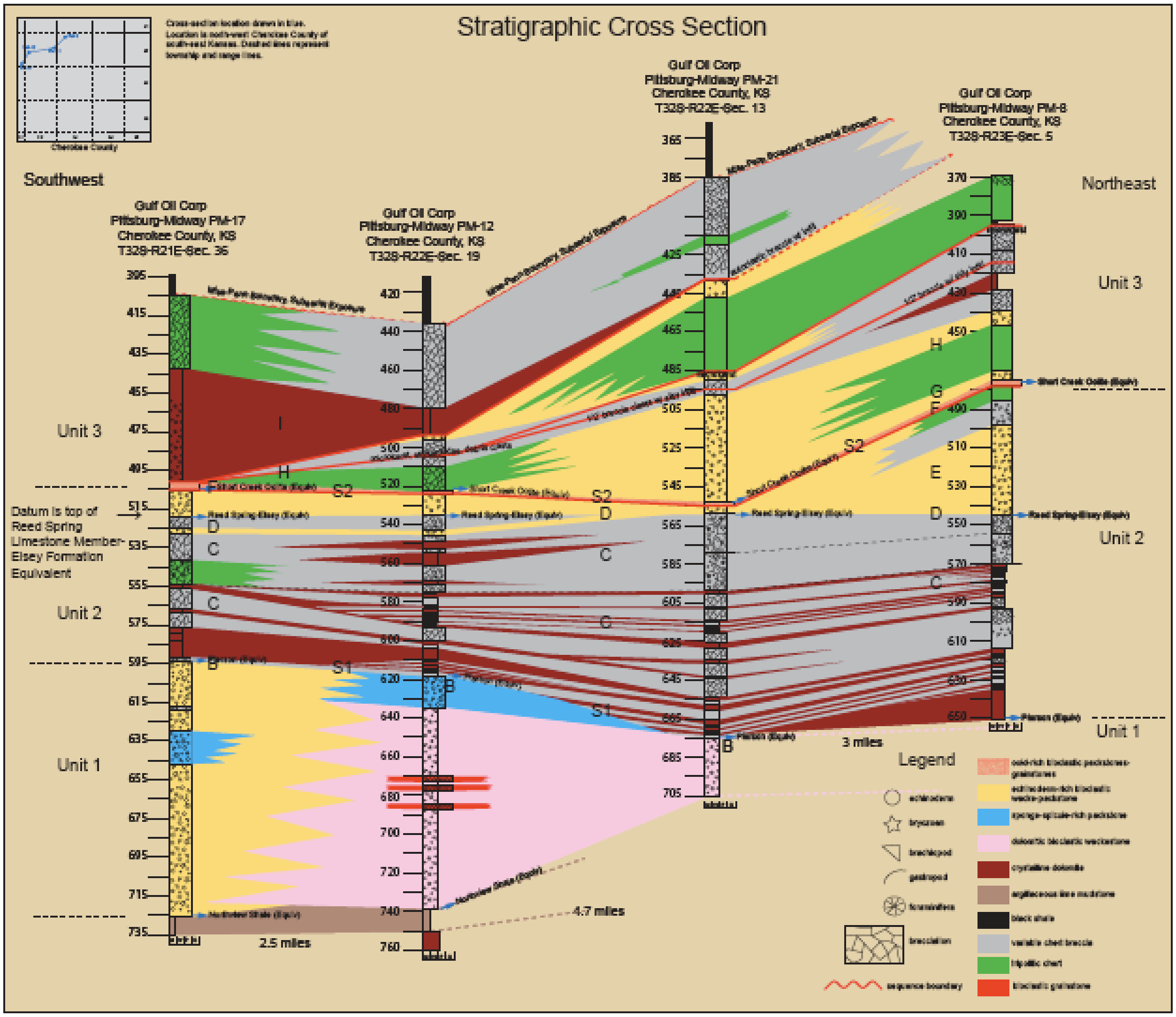

__Figure 2.__ NE-SW cross section illustrating geometries reflected by southward break in slope along the Osagean distally steepened ramp. Carbonate and chert facies are divided into three genetic units.

Controls on Character of Chalky Low-Permeability Reservoir Analog: Miocene Agua Amarga Basin

Robert H. Goldstein, Evan K. Franseen, and Craig Bennett

SUBSURFACE APPLICATION: Analog for deepwater Miocene exploration targets in southeast Asia, Niobrara, Eagle Ford, North Sea Chalks
STATUS: Focused-term project in progress
TIMING: Significant results to be reported to membership
FUNDING: Partial from University of Kansas, SEPM, AAPG, GSA

Purpose

Upper Miocene deposits of the Agua Amarga Basin in the Cabo de Gata region of Spain have a known sea-level history and preserved paleotopography (Figure 1). Field research will be conducted in the distal parts of this basin, where fine-grained, chalky carbonate strata are hypothesized to have multiple origins. Fine-grained, chalky carbonates elsewhere are typically lumped into simple designations of pelagic origin. Although such chalks constitute an excellent record of basin history, their fine-grained nature discourages interpretations of variability in facies development (Scholle et al., 1983). In the proposed research, fine-grained lithologies previously identified in the research area include facies with multiple origins, including: fine-grained turbidites, laminated diatomites, bioturbated diatomites, and other hemipelagic strata. Many of the deposits have been reworked by bottom currents. In the study area, controls on distribution of variable fine-grained facies are not yet understood, and evaluating such controls are the major focus of this project.

Project Description

As conventional high-permeability targets become increasingly scarce, the oil and gas industry must consider fine-grained low-permeability systems as reservoir, source, and oil shale resources. Miocene carbonates of the Cabo de Gata region in Spain provide a unique opportunity to study the controls on fine-grained chalky carbonate facies that preserve significant porosity and variable permeability. Production from such fine-grained carbonates is well known in North Sea regions and is an important secondary target in the Middle East. Many unconventional gas plays produce from low-permeability carbonates (e.g., Hugoton Field) and fine-grained organic-rich carbonates are an important potential oil shale resource. A focus on what controls the facies variations in such fine-grained carbonates should lead to stratigraphic models useful in exploration and production of hydrocarbon plays in similar fine-grained carbonate rocks.

Moreover, Miocene diatomites of southern Spain are analogs of source rocks and are one of the prime prospects for oil shale resources in the country. Age-equivalent facies in the nearby Lorca Basin have been touted as an excellent resource, yet there has been little exploration in similar basins nearby. We have discovered diatomites that appear superficially similar to those of the Lorca Basin, and the evaluation of total organic carbon and overall volume of the resource will help assessment of oil shale resources in Europe.

As chalky, fine-grained carbonates more and more are viewed as having reservoir potential, there is a great need in evaluating controls on distribution of the most prospective facies.

This project is focused on discriminating the details of depositional environments within deep water carbonate depositional systems (e.g., Dott and Bird, 1979; Cook and Mullins, 1983). Sedimentologic hypotheses for this project are that: (1) increased turbidite deposition occurs during times of low or dropping sea level, whereas pelagic strata are common during times of rising or high sea level (Franseen and Goldstein, 1999); (2) abundance of diatomites and preserved lamination are related to times of increased nutrient availability, either during times of high sea level and upwelling from deeper water or times of low sea level and runoff from the shore; (3) change in the basinal strata occurs in association with a shift in deposition from a heterozoan system to a photozoan system on the carbonate shelf, which may be due in part to climate change (Figure 2).

Approximately 25 high-resolution stratigraphic sections will be measured. Spatial relationships will be established by physically tracing stratal units, facies and surfaces laterally and marking on photomosaics. Ichnologic variations will be identified and quantified in the field. Approximately 250 samples will be collected for microfossil identification and for further facies description. Facies composition will be augmented by thin total, inorganic and organic carbon measurements made using a UIC Coulometric Titrator. Determination of carbonate to siliciclastic ratio, and XRF data will be will used to aid correlation with the local sea-level history.

The hypothesis of an observable warming trend will be tested by correlating the basinal strata to the platform and the local sea-level curve. It will be validated if shifts of the hemipelagic to benthic transition zone towards the platform are found to (a) exist and (b) be time equivalent to the warming-driven heterozoan to photozoan shift on the platform (at "SB 3"). Hypotheses that (1) turbidite abundance was controlled by sea level, paleotopography, and shelf position; and that (2) siliciclastic-rich turbidites were deposited more distally than carbonate-dominated ones, will be tested by (a) correlating these deposits to the local sea-level curve, (b) evaluating if the local paleotopographic controls found by Goldstein *et al*. (2012) hold, and (c) correlating to the evolving platform architecture identified by Sweeney (2016). The hypothesis that sea-level controlled bottom water oxygenation will also be tested using the local sea-level history. The hypothesis that sea level, depositional energy, and sediment medium controlled benthic seafloor activity will be tested by developing ichnocoenoses (following Savrda and Bottjer, 1994) and quantifying bioturbation according to the Ichnofabric Indices of Droser and Bottjer (1986). It will be validated if (a) variations in these environmental indicators can be tied to strata that mark specific depositional energy regimes/sediment medium consistencies, and (b) correlated to the local sea-level curve.

Deliverables

Deliverables include a Master's thesis, data bases, and presentations at KICC and other professional meetings. The study of the effects of sea level, nutrients, bathymetry and climate on facies distribution in the Agua Amarga Basin will increase understanding of the processes that control character of fine-grained deepwater carbonates. These data can be used to improve prediction of porosity and permeability in unconventional reservoirs, source-rock, and oil shale. Preliminary petrographic analyses indicate the presence of three microfacies identifiable by petrographic analysis (project completed by Becky Totten; Table 1; Figures 3-5). The study will produce a model for how sea level, climate, nutrients, and paleotopography, affect the distribution and rock character (including porosity and permeability) of fine grained chalky deposits, which can be used to enhance the understanding of similar distal basin chalky deposits in the rock record. As a reservoir analog, this will facilitate better prediction of porosity and permeability variations within similar strata, which can enhance the identification of potential targets within similar petroleum plays, such as the Niobrara, Eagle Ford, and North Sea.

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Lithofacies	**Fossil Assemblage and Clastics**	**Matrix**	**Fragmentation**	**Sorting**	**Sedimentary Structures**
***Globigerina/Diatom* facies**	Most of allochems are *Globigerina* foraminifera; also included are whole echinoderms, sparse mollusks and sponge spicules. Volcaniclasts may be present.	Diatoms comprise matrix. 30-80% matrix.	Very little to no fragmentation	Very good	Sparse parallel lamination (about 1 mm beds), common burrowing.
***Laminated Globigerina/Diatom* facies**	*Globigerina* foraminifera abundant; echinoderms, sparse mollusks and abundant sponge spicules. Sparse benthic foraminifera, such as *Miliolids* and biserial forms. Volcaniclasts may be present (in low abundance).	Diatoms comprise matrix. 20-70% matrix. Depends on lamina; Coarse, skeletal-rich lamina have 20-40%, skeletal-poor lamina have up to 70%.	Little fragmentation	Medium - good	Characteristic, distinctive fine lamination.
Skeletal facies	Foraminifera (both benthic and pelagic), echinoderms, sponge spicules, mollusks (bivalves, gastropods), and sparse bryozoans. Volcaniclasts typically present and may be abundant.	5-60% matrix. Few to no diatoms.	Characteristic fragmentation	Very poor - medium	May have normal grading, and may have burrowing.

Table 1. *Summary table of characteristics of three microfacies at El Palmar and Los Pollos. Data based on petrographic analysis of Becky Totten.*

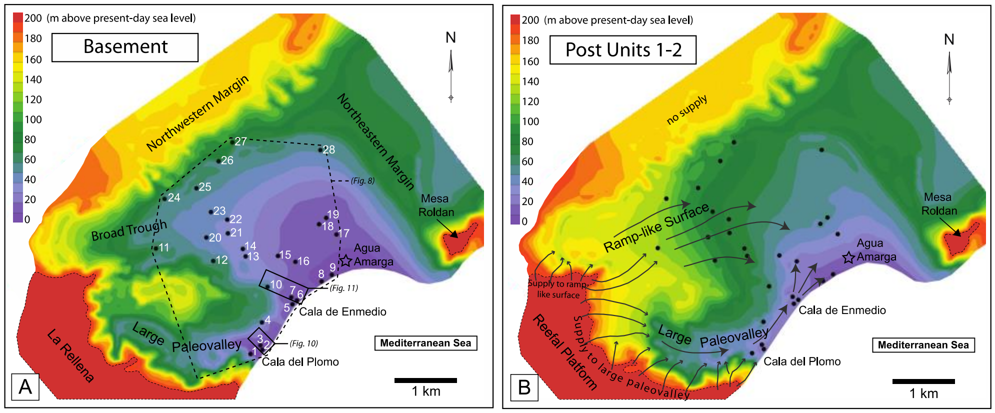

__Figure 1.__ Maps of the preserved paleotopography and extent of the Agua Amarga basin. Modified from Franseen and Goldstein (1999), Goldstein et al. (2013), Dvoretsky et al. (2014).

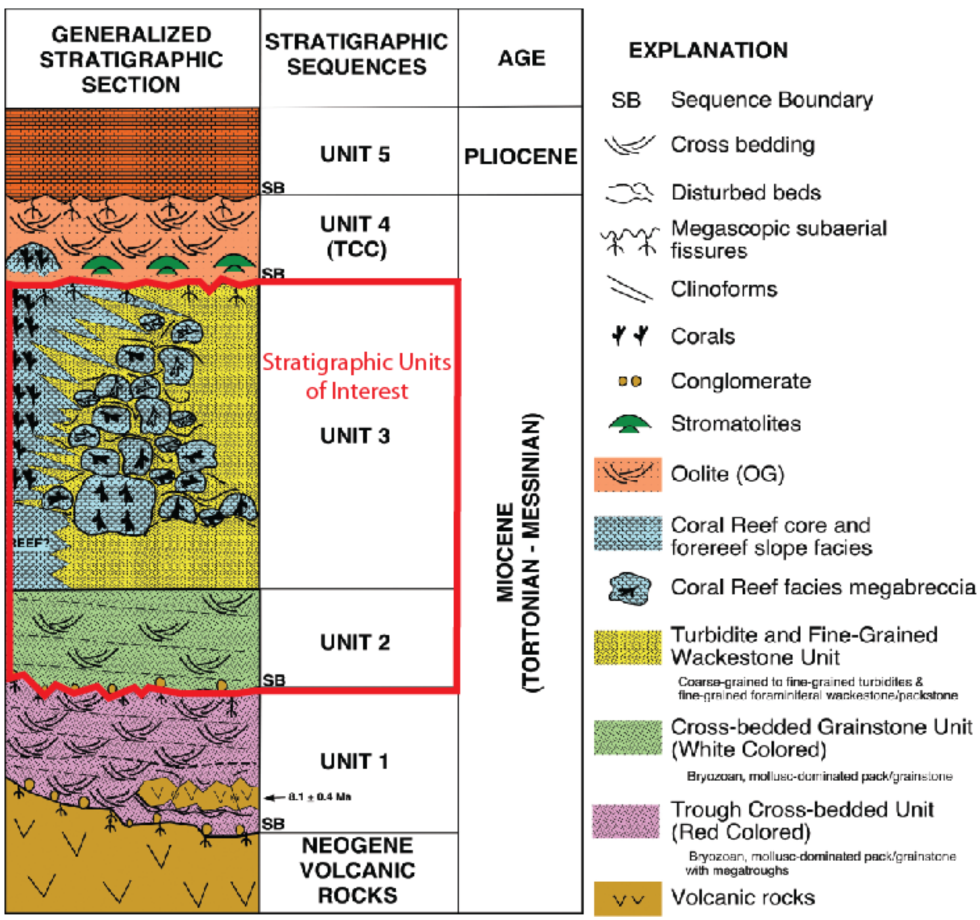

__Figure 2.__ Stratigraphic interval (box) of interest to this proposal. Modified from Franseen and Goldstein (1999).

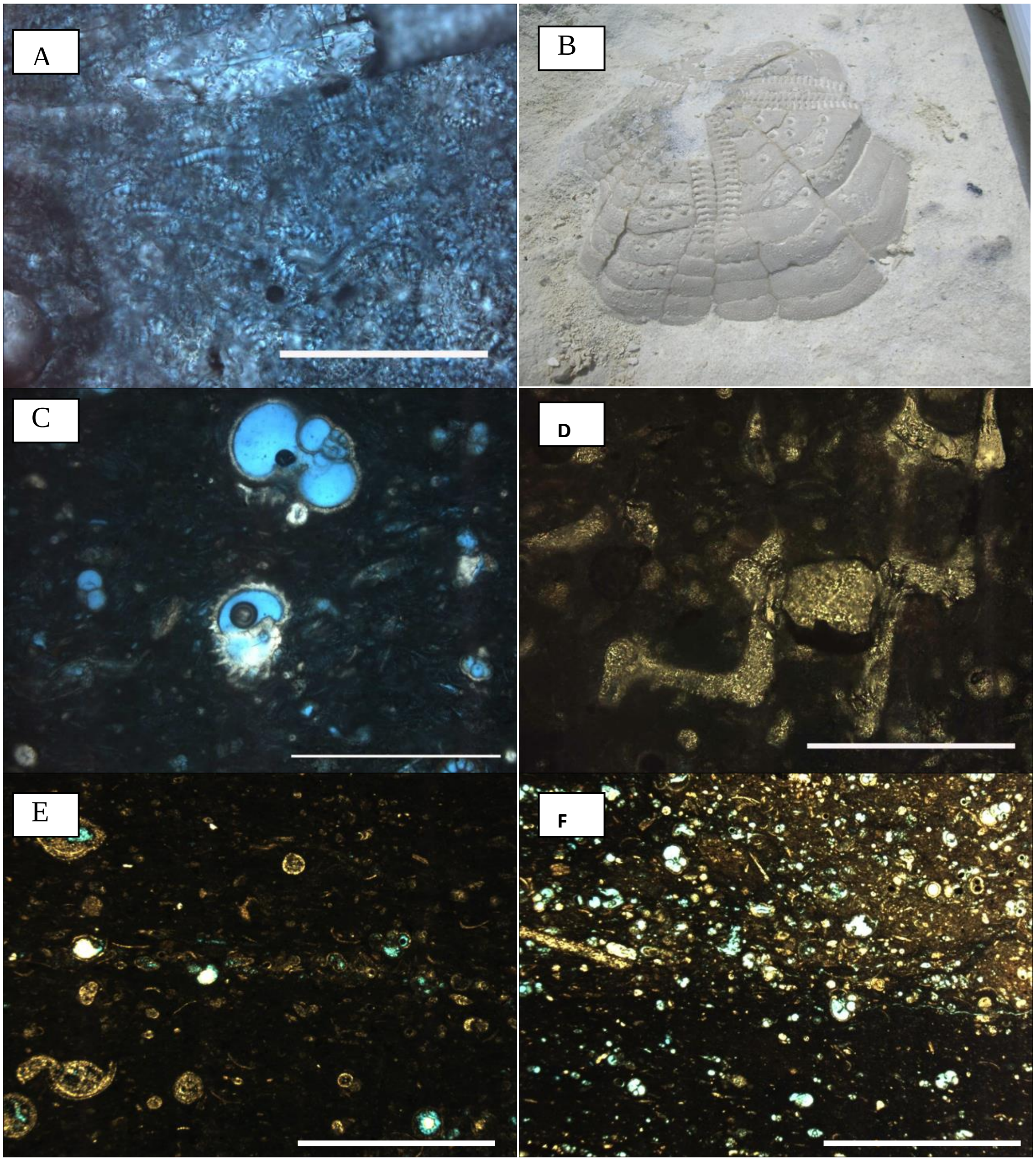

Figure 3. *A) Photomicrograph of typical* Globigerina*/diatom facies sample from Los Pollos showing diatoms in the matrix (sample LP6, Unit 2). Echinoid spine in northeast corner of picture. Scale bar is 0.1mm. B) Whole echinoid observed in Los Pollos outcrop (Unit 1). Diameter of echinoid is about 4cm. C) A well preserved* Globigerina *from the base of the El Palmar section, showing excellent preservation of delicate spines (sample EP2, Unit 1). Scale bar is 0.5mm. D) Sponge texture observed in sample LP5 from the lower Los Pollos section (Unit 1). Scale bar is 0.5mm. E) Fine laminae seen in sample EP10 from El Palmar (Unit 2). Thin layers of foraminiferal tests comprise the coarser laminae. Scale bar is 2.0mm. F)* Globigerina*/diatom sample from Unit 1 of El Palmar (sample EP2) showing a burrow with much coarser debris than the fine-grained diatomaceous matrix. Scale bar is 2.0 mm (after project by Becky Totten).*

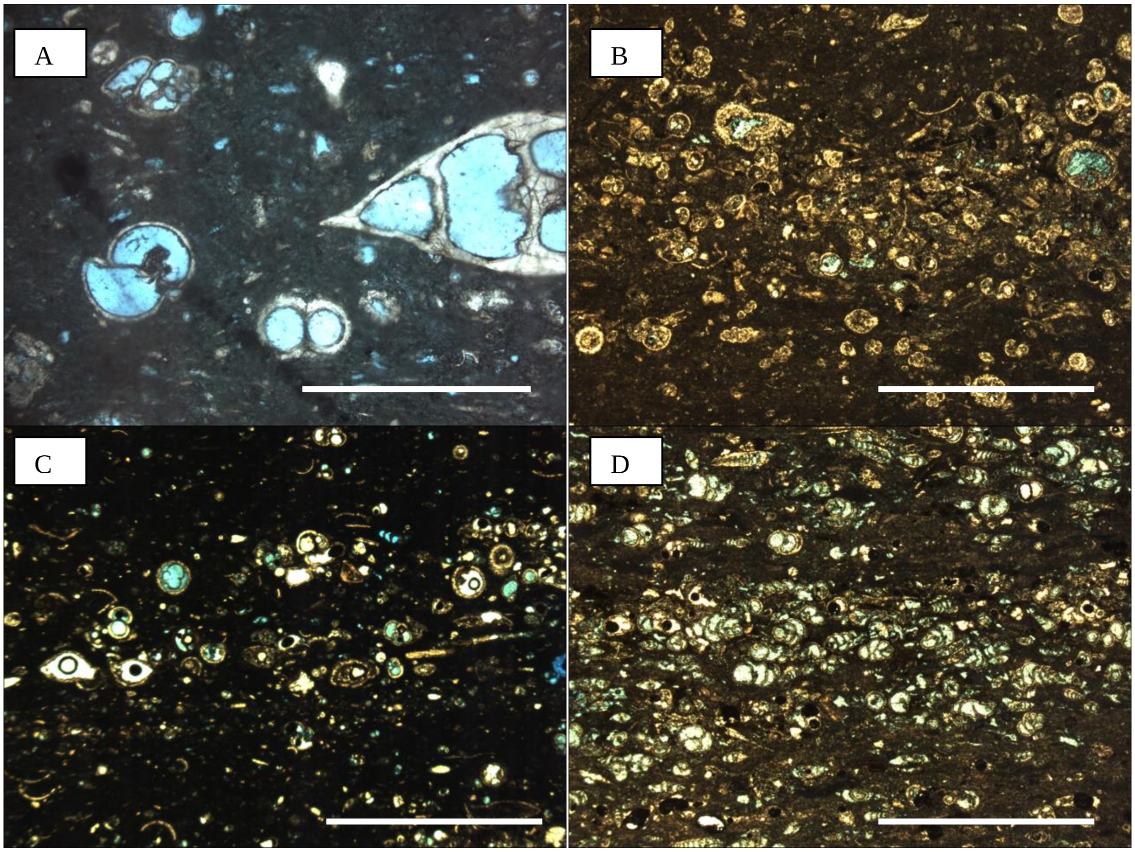

Figure 4. *A) Photomicrograph of typical laminated* Globigerina*/diatom facies sample from Los Pollos (sample LP11, Unit 3). Close up of matrix-rich lamina. It is very similar in nature to the* Globigerina*/diatom facies, but contains more benthics than the* Globigerina*/diatom facies. Scale bar is 0.5mm. B) Sample EP11 of El Palmar showing characteristic lamination in thin section. Scale bar is 2.0mm. C) Sample LP8 of Los Pollos also exhibiting distinctive lamination. Scale bar is 2.0mm. D) Sample EP12 from the top of El Palmar is an atypical sample, which is significantly abundant in triserial foraminifera. Notice distinctive lamination. Scale bar is 2.0mm (after project by Becky Totten).*

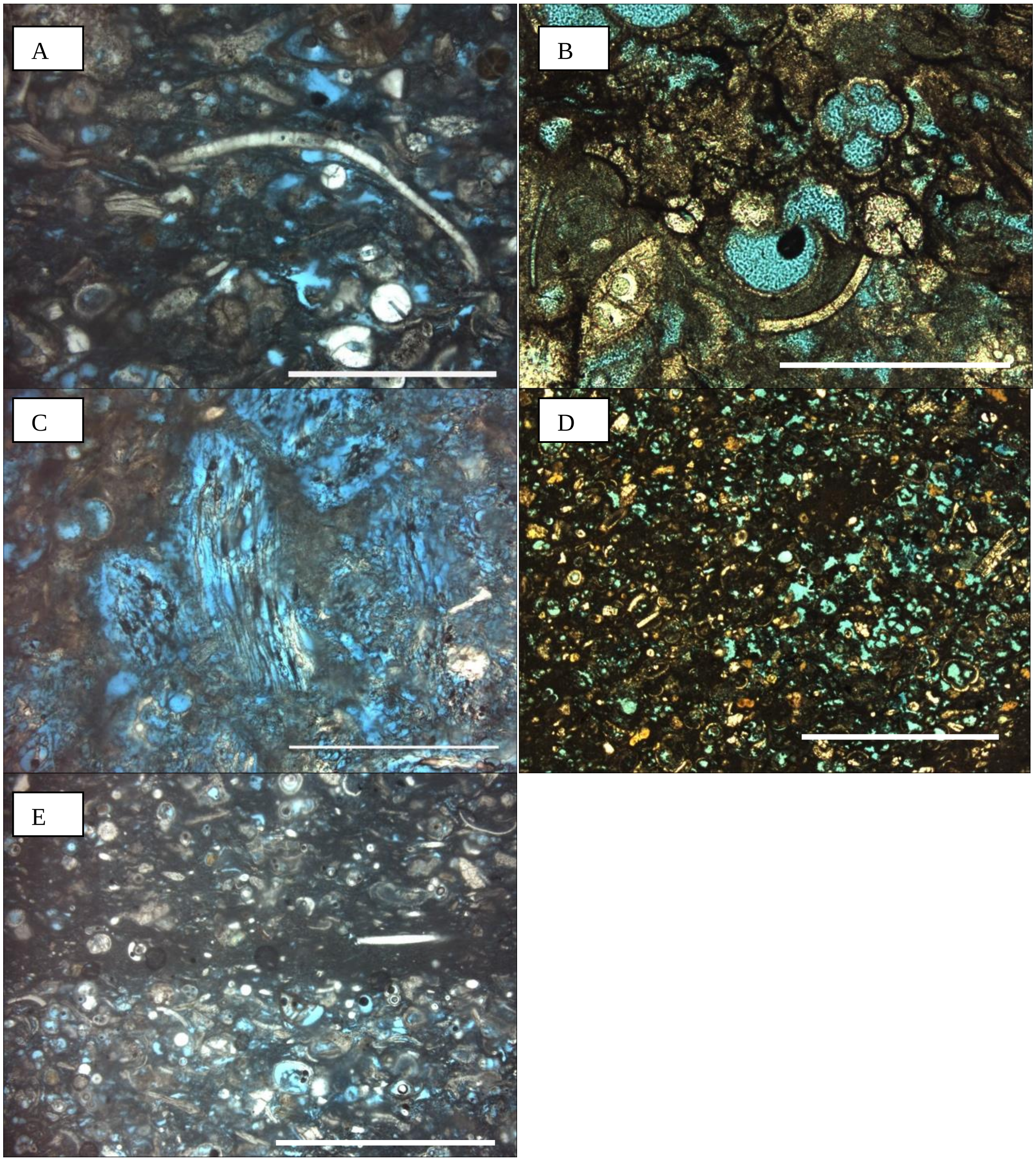

Figure 5. *A) Skeletal facies of Los Pollos showing high fragmentation and poor preservation (Unit 2). Scale bar is 0.5mm. B) Sample EP4 from El Palmar displaying extensive fragmentation and higher percentage of benthic fauna (Unit 1). Scale bar is 0.5mm. C) Skeletal Facies sample from Los Pollos with abundant volcaniclasts (LP4, Unit 1). Scale bar is 0.5mm. D) Sample LP2 from the base of Los Pollos showing abundant yellow volcaniclasts (Unit 1). Scale bar is 2.0mm. E) Another photomicrograph of sample LP7 from Los Pollos (Unit 2). Notice sharp contact of coarse bed with very fine bed. This microscopic lamination may reflect normal grading observed in outcrop. Scale bar is 1.0mm. (after project by Becky Totten)*

Diagenetic Controls on Porosity Evolution of Mississippian Strata in Well-Known and Emerging Plays in Oklahoma and Kansas

Robert H. Goldstein, Sahar Mohammadi, Hassan Eltom

SUBSURFACE APPLICATION: Mississippian Midcontinent reservoirs, Osage, Meramec, Chester, Sooner Trend, SCOOP and STACK, Golden Trend
STATUS: Beginning stages of project
TIMING: Project underway
FUNDING: KICC

Purpose

Mississippian strata comprise both well-known and developing unconventional and conventional plays in Kansas and Oklahoma (Franseen, 2006; Mazzullo et al., 2009; Mazzullo and Whilhite, 2010; Brown, 2014). Productive facies include biosiliceous deposits with microporosity, siltstones, dolomite, and limestone with variable architecture and porosity, depending on sequence stratigraphy and diagenesis.

This study will focus on diagenetic controls on porosity in Osagean, Meramecian, and Chesterian carbonates and biosiliceous deposits. In the Osage as an example, stratigraphically localized porous facies are hypothesized to be associated with: 1) late and early fluid flow along stratigraphic horizons, highly fractured intervals, and fault damage zones; 2) localized diagenetic alteration in sponge spicule mounds; and 3) localized reflux dolomitization (Ritter and Goldstein, 2012; Ramaker et al. 2014; Montalvo, 2015; Grammer et al, 2018; Mohammadi et al. 2018a, b; Goldstein et al. 2018). Additional sequence stratigraphic and diagenetic variables are added in the Meramec and Chester. ***This study will improve understanding of porosity evolution in biosiliceous and carbonate deposits, focusing on porosity distribution and diagenetic events in Mississippian strata of Oklahoma, and extending this understanding into Kansas*. *It will develop an understanding for stratigraphic and structural controls on diagenetic alteration as a means of developing predictive models for reservoir properties.***

Project Description

The goal of this study is to understand the diagenetic processes by which the porosity is enhanced or reduced in the Mississippian of Oklahoma, and accordingly, develop models that can help predict porosity distribution. Understanding how diagenesis controls porosity in biosiliceous and carbonate strata is important for hydrocarbon exploration and development in Midcontinent reservoirs in general. This project includes several specific objectives highlighted below:

- Sampling strategy will be based on cross sections and interpreted stratigraphic control as well as structural setting and potential fluid flow pathways. It will relate directly to the project *Superhighways for Hydrothermal Fluid Flow in the Midcontinent: Structural and Stratigraphic Controls on Thermal Structure, Flow Rate, and Reservoir Properties* by sampling an area within and an area outside of a major structural conduit for hydrothermal fluid flow in Oklahoma. This conduit has evidence for significant alteration by hydrothermal fluids, and could have been one of the pathways by which hydrothermal fluids were focused locally in Oklahoma and northward into Kansas.

- Thin sections will be prepared from the selected samples and will be used for transmitted light and UV petrography to point count mineralogy, carbonate and siliceous constituents, cements (replacement silica, silica cements, calcite and dolomite), pore type and size. The thin sections will be stained with alizarin red S to differentiate mineralogy among quartz calcite and dolomite. From this, we will construct a full petrographic description, which will eventually result in creating a paragenetic sequence of diagenetic events in Mississippian biosiliceous and carbonate strata.

- Thick section samples will be prepared for fluid inclusion analysis. The fluid inclusion petrography and microthermometric analyses will be conducted using low-temperature techniques outlined by Goldstein and Reynolds (1994) and will be performed using a Linkam THMSG 600 stage. Fluid inclusion and microthermometric analyses will provide information about temperature and salinity of mineral precipitation and fluid migration.

- Stable and radiogenic isotopes (C, O, Sr) will offer additional lines of evidence to determine timing, temperature and fluid history for the paragenetic sequence of calcite and dolomite.

Deliverables

This study will provide a paragenetic framework for Mississippian strata in areas of Oklahoma. Geochemical analyses will establish timing in relation to stratigraphic setting and structure evolution, temperature, and fluid composition. This will be used to develop predictive models of porosity evolution for Mississippian biosiliceous and carbonate strata to understand diagenetic controls on reservoir properties in the Midcontinent. The models are expected to answer specific questions about stratigraphic and structural control on reservoir properties. In particular, this project will provide new insights on the impact of hydrothermal fluid flow on alteration of reservoir properties in the Mississippian, developing a structural and stratigraphic model for prediction of enhanced reservoir.

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Phase Behavior of Confined Fluids in Unconventional Reservoirs

Gang Yang and Laura Li

SUBSURFACE APPLICATION: Haynesville, Niobrara, Permian, Bakken and Marcellus Shale Play
STATUS: Focused-term project in progress
TIMING: To be completed in the future if funded
FUNDING: None

Purpose

The objective of this project is to develop a modified pressure-volume-temperature (PVT) model to investigate the phase behavior of confined fluids in nano- and micro-pores of unconventional reservoirs. Its impact on the field-scale production will be quantified via reservoir simulation.

Project Description

Phase behavior of confined fluids deviates significantly from that of bulk fluids (Gelb et al., 1999). The confinement effect resulting from increasing molecule-wall interaction and capillary pressure is non-negligible for carbonate-rich shale reservoirs and is widely referred as the direct reason for the phase behavior deviation (Travalloni et al., 2014; Sandoval et al., 2016).The classical PR EOS based on bulk fluids is inapplicable for fluids in carbonate-rich shale reservoirs because it cannot reflect the unique thermodynamic properties of confined fluids, such as the suppressed bubble-point pressure and critical property shift (Alharthy et al., 2013). Hence, an extended PR EOS model with incorporation of both molecule-wall interaction and capillary pressure are expected to be proposed in order to predict the phase behavior of confined fluids more accurately. Moreover, it has been found that pressure-volume-temperature (PVT) properties shift under confinement effect have significant impacts on the predicted production profile and the ultimate recovery (Sanaei et al. 2014; Zhang et al. 2017).

1. Molecule-wall interaction

Since the molecule size of confined fluid is comparable to the pore size, as demonstrated in Figure 1 (Alfi et al., 2016), the molecule-wall interaction, which is usually neglected for bulk fluids, has significant effect on the phase behavior of confined fluids (Derouane, 2007). Hence, a molecule-wall interaction term is newly introduced to extend the classical Peng-Robinson Equation of State (PR EOS) model. On the basis of data collected from both experiments and molecular simulations, a correlation between the shifted critical temperature data and the dimensionless pore size has been developed and incorporated into the extended PR EOS to determine the molecule-wall interaction term. The expressions to calculate the compressibility factor (Z factor) and fugacity for the extended PR EOS are accordingly derived.

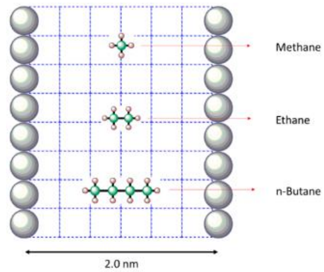

Figure 1. *The scale of light hydrocarbons when confined in a pore size of 2 nm (Alfi et al., 2016)*

2. *Capillary pressure*

Erroneous results can be obtained if the capillary pressure is not considered for confined fluids flash calculation into nanoscale pores (Nojabaei et al., 2013). Therefore, both the pressure of vapor phase and the pressure of liquid phase are incorporated into the flash calculation with the extended PR EOS, the difference between those two pressures is the capillary pressure. It is assumed that the liquid phase is the wetting phase and the vapor phase is the non-wetting phase. The flash calculation algorithm with consideration of capillary pressure is proposed.

3. Model Validation

Experimental data of both single- and multi-component fluids are collected to validate the extended PR EOS model under different confinement effect (different pore sizes). These data include the suppressed saturation pressure (single-component fluids), shifted critical temperature (single-component fluids), and the suppressed dew-point pressure (multi-component fluids). Compared with the data of multi-component fluids, the data of pure fluids are more abundant.

4. Impact on field-scale production

The shifted PVT properties predicted by the extended PR EOS are then applied in building the field-scale numerical simulation model of the carbonate-rich shale reservoir. Production profile and ultimate recovery are predicted and compared with those obtained without PVT property deviation (calculated by the classical PR EOS).

Deliverables

This project will produce an extended PR EOS that is applicable to describe the shifted PVT properties of confined fluids in nanopores. The predicted results will provide instructive insights into optimizing the field production of carbonate-rich shale reservoirs.

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Gas Transport in Shale Matrix Coupling Multilayer Adsorption and Pore Confinement Effect

Di Chai and Laura Li

SUBSURFACE APPLICATION: Haynesville, Niobrara, Permian, Bakken and Marcellus Shale Play
STATUS: Focused-term project in progress
TIMING: Results currently available to membership
FUNDING: None

Purpose

The goal of this project is to develop a gas transport model characterizing real-gas flow in multi-scale organic and inorganic pores of carbonate-rich shale reservoirs. Three mechanisms are well coupled to mathematically describe the full flow spectrum including continuum flow, slip flow, transition flow, and Knudsen diffusion.

Project Description

Carbonate-rich shale reservoirs which are widely distributed in North America such as the Haynesville and Niobrara shales have a complex pore structure associated with both organic and inorganic matrix (Loucks et al, 2009). Organic pores commonly are smaller than 50 nm. The aggregates of carbonates in shale can form the inorganic macropores greater than 50 nm. The gas transport in pores is a multi-mechanism-coupling process. The quantitative description of gas transport in matrix-related pore systems is a key issue for successful carbonate-rich shale gas development.

1. Conceptual Layered Model

A conceptual model is developed as illustrated in Fig. 1. The space in the single straight nanocapillary can be separated by the effective radius R_e into two flow zones, which are a free gas flow zone in the central space (i.e., the space within the red cylindrical capillary) and a surface diffusion zone in the outer annular space (i.e., the space constrained by the effective radius R_e and capillary radius R_0). Note that the volume in the outer annular zone is occupied by multilayer adsorbed gas, of which the amount is significantly underestimated in analytical calculations with the existing models due to the monolayer adsorption assumption.

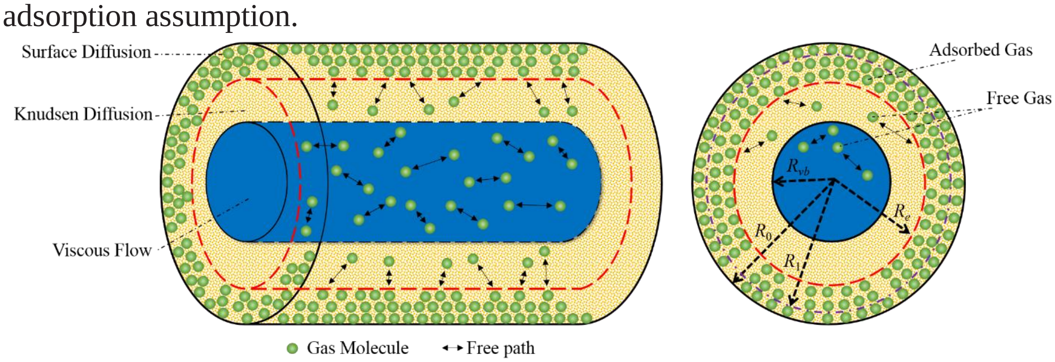

Figure 1. *Schematic diagram of the conceptual layered model of a straight capillary tube*

2. *Characterization of Roughness, rarefaction, pore confinement effect and real gas effect*

Considering the fractal dimension of the pore surface, the structural heterogeneity of the media can be quantified by using a fractal dimension coefficient, which is between 2.0 and 3.0 indicating changes from a smooth surface to a space-filling surface. *A roughness coefficient represents the coupled effects of surface fractal dimension, effective pore size, and gas molecule size (Darabi et al. 2012). In addition,* Yang et al. (2018) have proposed a modified PR EoS by considering both critical property shift and the non-negligible capillary pressure to accommodate the nanoscale pore-confinement. *The* compressibility factor is considered and incorporated into the developed gas model to reflect the real gas effect.

3. Model Validation

The model can be validated for methane transport from two scales: a single straight organic nanocapillary (pore-scale) and a shale rock core sample (core-scale). The molecular dynamics (MD) simulation data will be collected to validate the methane apparent permeability in organic nanocapillary under shale reservoir pressures from 5 to 50 MPa. The pulse decay experiment on an Eagle Ford shale core sample has been conducted with the experimental error of 5% and a lognormal pore size distribution using nonlocal density functional theory (NLDFT) has been obtained (Alnoaimi and Kovscek, 2013). Their data are collected to validate the methane apparent permeability in up-scaled porous media. The newly developed model will be compared with four well-recognized existing analytical models to further demonstrate the superiority of this work.

Deliverables

This project can deliver an analytical gas transport model for carbonate-rich shale reservoirs. The model can be coupled with hydraulic fracturing models in commercial simulation software to assist reservoir history matching and benefit long-term gas production predictions.

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Lattice Boltzmann Simulation of Fluid Flow in Shale Nano-Pores

Sherifa Cudjoe and Reza Barati

SUBSURFACE APPLICATION: Chattanooga, Woodford, Marcellus, Bakken, Eagle Ford, Haynesville, Utica, Permian and Niobrara/Turner.
STATUS: Project Proposed
TIMING: To be completed in the future if funded
FUNDING: Not funded

Purpose

The objective of this project is to simulate two-phase flow of oil and gas using a compositional Lattice Boltzmann Method (LBM) to effectively capture the pore-wall effects at a molecular level in order to accurately predict rock properties such as permeability and relative permeability used in the evaluation of the huff-n-puff process in shales.

Project Description

Unconventional shale resources are predominantly exploited over the years due to their great potential to increase the total hydrocarbon production mainly in North America and other parts of the world. Understanding of the complex pore network coupled with pore wall effects at the nano-scale plays an important role for these important resources to accurately simulate fluid flow and eventually optimize hydrocarbon production in these reservoirs. Rock-fluid interaction is vaguely known in these rocks and it is subject to history matching. A two-phase, compositional LBM is recommended to estimate the rock-fluid properties for these rocks.

FIB-SEM: Combining SEM column with a Ga-FIB, thin serial slices of a region of interest (ROI) will be milled away and SEM pictures will be taken of each slice. The resulting stack of 2D SEM images can then be reconstructed into 3D volume to study porosity, connectivity and permeability of a shale subsample at ~5nm resolution. The extracted pores through image segmentation will be exported to an open access LBM code, which will be modified to incorporate the pore wall effects and diffusion.

Lattice Boltzmann Method (LBM): The LBM as a numerical method for simulating viscous fluid at molecular scale, will be used on the extracted pores to effectively model rock properties such as Knudsen diffusion, slip flow, adsorption, surface diffusion as well as the rock fluid properties such as relative permeability. These non-zero flow enhancements at the pore walls will be accurately captured.

Two-Phase flow: The LBM will be used on a lattice with fluid/fluid and fluid/solid interactions to model interfacial tension, relative permeability and wettability using the Shan-Chen two phase model [2]. The simulated relative permeability and capillary pressure curves will be compared to either analytical predictions or experimental measurements such as capillary pressure and unsteady- or steady-state relative permeability measurements.

Deliverables

This project will produce a comprehensive pore-scale simulation model, where the fluid flow mechanisms are clearly captured and rock properties easily determined through LBM simulations. The relative permeability curves will be provided to commercial softwares to accurately simulate the huff-n-puff process. This would eventually bridge the gap in understanding of uncertainty in unconventional reservoirs, as well as optimize hydrocarbon production from these reservoirs.

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Chemostratigraphy in Unconventional Microporous Limestone: Accounting for diagenesis in a clay-rich carbonate (e.g., Niobrara)

Franek Hasiuk (Kansas Geological Survey)

SUBSURFACE APPLICATION: Basic research into diagenetic paradigm of microcrystalline calcite in clay-rich environments
STATUS: Awaiting funding
TIMING: Upon funding
FUNDING: Awaiting funding

Purpose

- To reduce uncertainty regarding chemostratigraphic correlations
- To document paragenesis of the microcrystalline rock textures that host micron-size pores

Project Description

"Unconventional" hydrocarbon resources require new ideas for exploration and new technologies for production. Many such deposits occur in fine-grained mixed carbonate-clastic strata. While much work has been done to characterize fine-grained carbonates (e.g., Fullmer et al., 2014, Kaczmarek et al., 2015, Hasiuk et al., 2016), we do not know how our current models are affected by increasing clay content. In addition, much interest has arisen from using bulk elemental and isotopic chemistry of unconventional rocks for the purposes of correlation of strata. This technique is founded on the idea that fine grained carbonates do not undergo significant diagenesis. A significant need exists to reconcile the diagenesis of fine-grained carbonates with chemostratigraphic techniques.

My long-term goal is to understand how microporosity and the rock matrix that hosts it forms and undergoes diagenesis. This project seeks to examine samples of Niobrara formation clay-rich, fine-grained limestone (Hattin, 1982) to document the formation and diagenesis of the matrix calcite in terms of its morphology and chemistry to test whether chemostratigraphic correlations are justified.

We will construct carbon isotope chemostratigraphic correlations from Rebecca Bounds #1 Core (Greeley County, Kansas, Zambito et al., 2012) to the producing area in Cheyenne County, Kansas, as well as another correlation from Cheyenne County to the outcrop belt in Smith/Jewell Counties, Kansas (Figure 1). In addition to geochemistry, SEM images and high resolution SEM-EDS chemical data will be collected to establish the paragenesis of the fine-grained carbonates. ***These correlations will allow us to test the hypothesis that carbon isotope chemostratigraphic profiles can be affected by diagenesis.*** I am well qualified to undertake the research based on my background in both the diagenesis of fine-grained limestone (e.g., Kaczmarek et al., 2015, Hasiuk et al., 2016) as well as my work in chemostratigraphy (e.g., Ludvigson et al., 1996).

I expect that this research will clarify how calcite microcrystals form and undergo diagenesis in a clay-rich environment, while reducing uncertainties with chemostratigraphic correlation. It may also identify prospective regions for shallow gas production in the vicinity of Cheyenne County (Figure 2).

Deliverables

- Publications and presentations of research results
- Field trip and core workshop on Niobrara lithologies
- Geochemical data
- Core analysis data (helium porosity/permeability, mercury pore throat size distributions)
- SEM images and FIB-SEM volumes of microcrystalline textures

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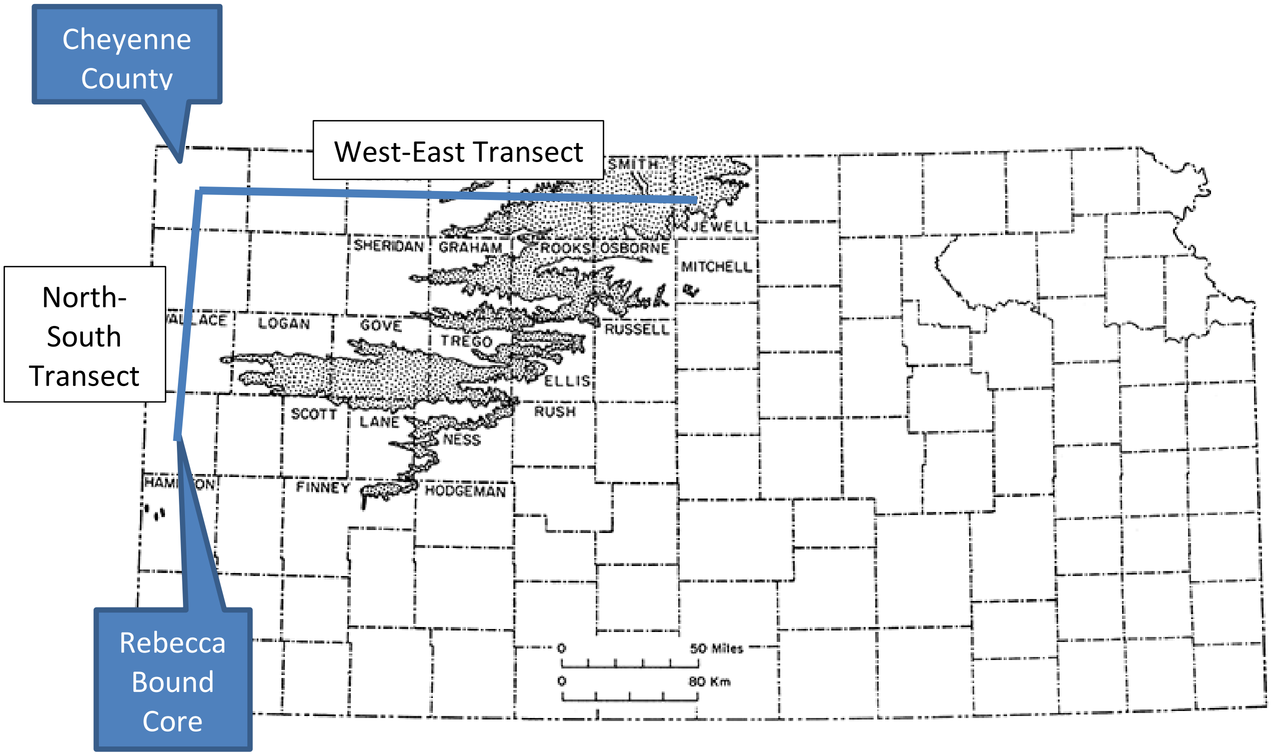

Figure 1. *Map of Niobrara Outcrop Belt as well as Rebecca Bound Core and Cheyenne County production in Kansas (after Hattin, 1982).*

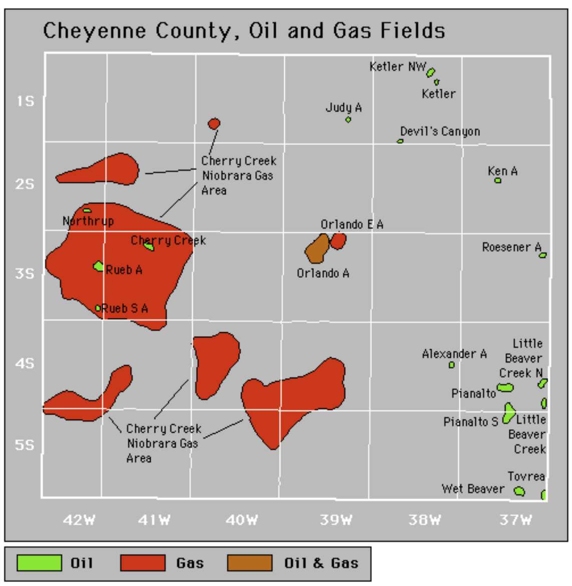

Figure 2. *Map of petroleum production in Cheyenne County (Kansas). Gas production is from shallow biogenic gas in the Niobrara Formation. After KGS website (http://www.kgs.ku.edu/PRS/County/abc/cheyenne.html).*

Ichnology of the Upper Cretaceous Greenhorn and Niobrara Formations of the Amoco Production Company Rebecca K Bounds #1 Well, Greeley County, KS

Stephen T. Hasiotis, Adam M. Jackson, and student

SUBSURFACE APPLICATION: Upper Cretaceous Greenhorn and Niobrara formations reservoir and source rocks in oil and gas fields in the Denver-Julesburg basin
STATUS: Phase 1 of this project; expanding on previous work.
TIMING: Data being collected; student dissertation research underway; results being reported to KICC (2015, 2016) as they are produced.
FUNDING: Seeking funding from KICC sponsors; opportunity for additional funding for spinoffs for more research; 2 (MS student)–4 (PhD student) years

Purpose

Rhythmically bedded marlstone and limestone in the Greenhorn and Niobrara formations contain distinctly different trace-fossil assemblages (ichnocoenoses). Marlstone is often laminated with bioturbation fabrics of 1–2 (ichnofabric index; *ii*) or 0–1 (bioturbation intensity; *bi*), whereas limestone is highly bioturbated commonly with *ii* and *bi* of 3–4. Marlstone ichnocoenoses consists of small *Planolites*, *Chondrites*, and *Teichichnus*. Limestone ichnocoenoses consists of *Planolites*, *Zoophycos*, *Teichichnus*, and *Thalassinoides*. The greater degree of bioturbation in the limestone may enhance the porosity and permeability compared to that of the marlstone. ***The purpose of this study is understand the distribution of bioturbation patterns coupled with sedimentary structures in the Upper Cretaceous Greenhorn and Niobrara formations of the Amoco Production Company Rebecca K Bounds #1 to (1) interpret environments of deposition, (2) reconstruction oxygenation profiles in the basin (e.g., alternation of oxic [limestone) and dysoxic [marlstone] conditions), and (3) investigate differences in micro- and macropermeability produced by the variety of trace fossil morphologies in core.***

Project Description

Organic carbon-rich shale, marlshale, and marlstone can host significant hydrocarbon resources. Although trace fossils and bioturbation patterns have been used as benthic oxygen indicators in these lithologies, a high-resolution study of changes in depositional conditions using ichnology has not been done for the Niobrara and Greenhorn formations. The goal of this project is to ichnologically assess the depositional conditions for the Upper Cretaceous Greenhorn and Niobrara formations of western Kansas. The purpose of this project is to describe the ichnology of the Greenhorn Formation, with emphasis on the (Cenomanian–Turonian) Bridge Creek Limestone Member.

The Upper Cretaceous Greenhorn Formation has been studied due to its organic carbon content, up to 5.1% (Pratt, 1984), and distinct traceable beds across the Western Interior Seaway (Hattin, 1971). The major traceable beds are bentonites, which have been used to erect lithochronozones and estimate rates of deposition (Hattin, 1985; Elder et al., 1994). This study uses the Amoco Production Company Rebecca K. Bounds #1 Well, from Greeley County, Kansas (Figure 1), where the Bridge Creek Limestone Member (BCLM) of the Bounds core is 26.2 m thick with 99.9% recovery.

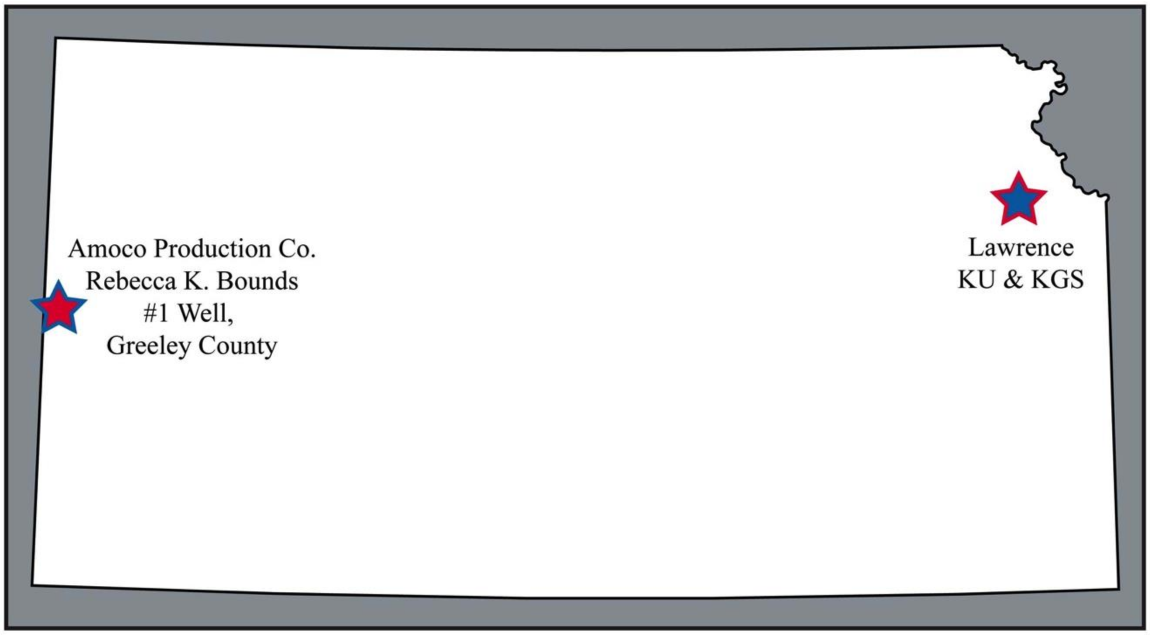

***Figure 1**. Location of Amoco Production Company Rebecca K. Bounds #1 well from Greeley County, Kansas.*

The Greenhorn Formation, deposited during a transgressive systems tract, consists of the BCLM that overlies the Heartland Shale Member and basal Lincoln Limestone Member. In western Kansas, the BCLM is dominated by marlstone with decimeter-scale limestone beds. The marlshale and marlstone are laminated with little to no bioturbation, whereas the limestone is highly bioturbated. Intense bioturbation, that in a few limestone beds, produces mottled patterns in which distinct burrow morphologies are unrecognizable. The laminated units have been interpreted as zones where the benthic oxygen content was very low (Pratt, 1984; Savrda, 1998).

The lower half of the BCLM (from ~289 to 302 m) contains well-developed, rhythmically bedded cycles of marlstone and limestone that show distinct differences in type, size, and intensity of bioturbation. In the thinly laminated marlstone, trace fossils are often sparsely distributed with a ii of 1–2 and a bi of 0–1, and are limited to a few ichnogenera. The marlstone ichnocoenoses consist commonly of small Planolites, Chondrities, and Teichichnus (Figure 2). This is in contrast to the highly bioturbated limestone, with a ii and bi of 3–4. A few limestone beds appear massive due to bioturbation (ii and bi of 6). The limestone ichnocoenoses contain *Planolites*, *Teichichnus*, *Thalassinoides*, and *Zoophycos* (Figure 3).

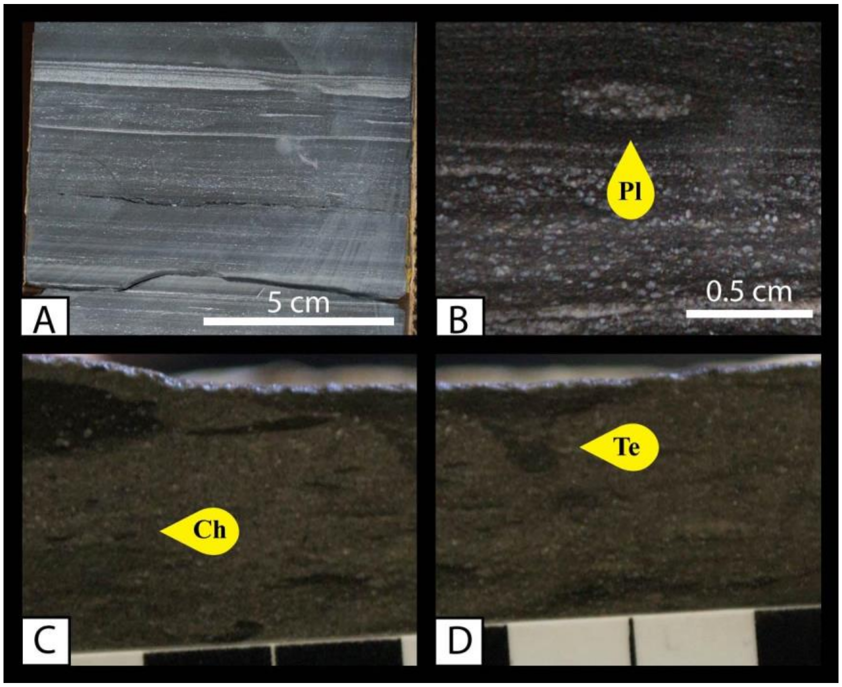

***Figure 2**. Common trace fossils of the marlstone of the Bridge Creek Limestone Member of the Greenhorn Formation. A) Laminated bedding with few to rare burrows in marlstone. B)* Planolites. *C)* Chondrites. *D) Teichichnus. From the Amoco Production Company Rebecca K. Bounds #1 well. Ruler bars 0.5 cm.*

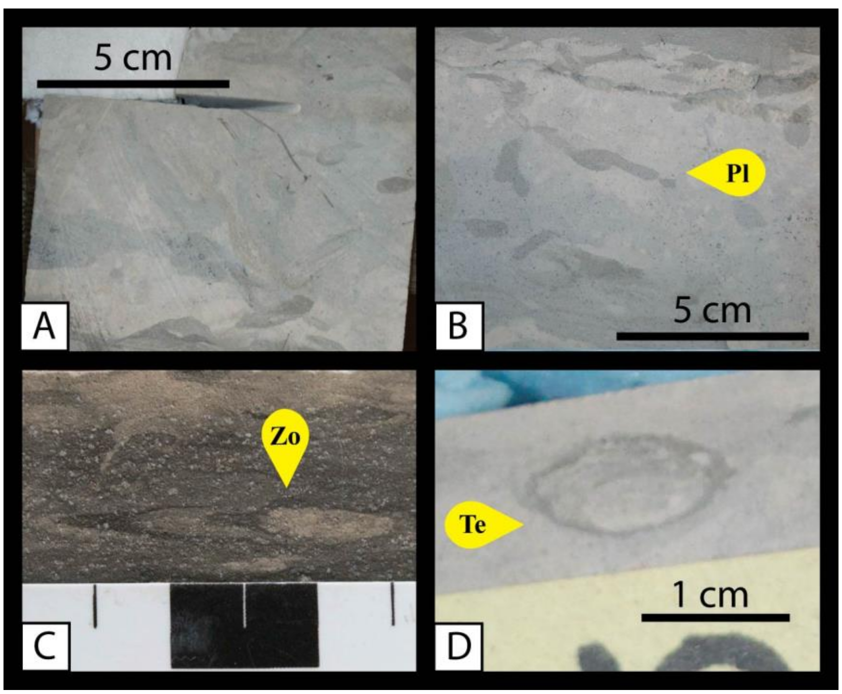

***Figure 3**. Common trace fossils of the limestone of the Bridge Creek Limestone Member of the Greenhorn Formation. A) Burrow mottling common in limestone. B)* Planolites. *C)* Zoophycos. *D)* Teichichnus. *From the Amoco Production Company Rebecca K. Bounds #1 well. Ruler bars 0.5 cm.*

To further this preliminary research (phase 1), we will analyze the ii and bi of the Greenhorn and Niobrara formations in Amoco Production Company Rebecca K Bounds #1 housed in the Core Barn at the Kansas Geological Survey in Lawrence, Kansas. We will make a bed-by-bed assessment of the trace fossil diversity, tiering depth, and intensity with respect to the lithofacies in which they occur, including differences in grain-size distribution, size, and sorting and facies relations. Sediment from burrow fills will be compared to the surrounding matrix to determine how burrow fills affect local porosity and permeability. We will perform minipermeameter analysis of the bioturbated intervals vs. nonbioturbated intervals, as well as attempt to distinguish differences in bioturbated intervals composed of large diameter vs small diameter burrow systems. As part of this analysis we will also explore the permeability of different trace fossil morphologies with respect to the ii and bi, in comparison to the background texture of the host sediment vs. similar lithofacies with no bioturbation. The purpose of this is to determine the effects of bioturbation on postdepositional modification of effective porosity and vertical permeability. All of these data on bioturbation patterns will be tied to the stratigraphic variation in lithofacies in each formation to build ichnocoenoses (trace fossil communities) and ichnofacies models to understand the relationship between grain size, lithofacies, biogenically mediated porosity and permeability trends. Through this systematic analysis, we expect to find subtle though marked differences in grain size, sorting and type, sedimentary structures and ichnology, and effective porosity and permeability that characterize the pay zones of this gas-bearing unit.

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Enhanced Oil Recovery and CO_2 Flooding/Sequestration in Carbonates

The University of Kansas Tertiary Oil Recovery Project (TORP) has an extensive portfolio of research on improving oil recovery from carbonate reservoirs. Staffing in TORP is funded by the State of Kansas. Students and faculty in the Department of Chemical and Petroleum Engineering, and Department of Geology interact extensively in their courses, learning skills directly applicable to the oil and gas industry. Engineering staff of TORP and faculty in Chemical and Petroleum Engineering specialize in dual porosity/fractured reservoir systems in carbonates. Interdisciplinary studies among TORP, Chemical and Petroleum Engineering, the Department of Geology, and KGS are exploring a wide range of avenues related to enhance oil recovery and CO_2 sequestration in carbonates. Examples of some current and pending projects include:

Seismic Imaging of CO_2 EOR in the Mississippian Reservoir, South-Central Kansas

George Tsoflias, Lauren Haga, Lynn Watney

SUBSURFACE APPLICATION: Assessment of seismic monitoring of a CO_2 injection in the Mississippian for enhanced oil recovery
STATUS: Project completed and not yet published
TIMING: Significant results to be reported – Results currently available to membership
FUNDING: Partial from United States Department of Energy

Purpose

Carbonate reservoirs are heterogeneous and the distribution of properties controlling the flow of fluids is difficult to predict (Watney et al., 2001). Seismic characterization of carbonate reservoirs is challenging and the subject of extensive research. Work reported by KICC at Wellington field in south-central Kansas identified characteristic relationships between Mississippian reservoir properties (thickness, porosity, fracture density and orientation) and seismic attributes (Amplitude Variation with Offset – AVO, P- and S-Impedance, seismic anisotropy - AVAZ), and developed seismic inverse workflows that predicted Mississippian properties. The project extends prior work by evaluating the effectiveness of seismic imaging for monitoring CO_2 enhanced oil recovery (EOR) in the Mississippian reservoir at Wellington field.

Project Description

Time-lapse seismic analysis is used to assess the effectiveness of seismic imaging methods (pre- and post-stack) for monitoring a CO_2 injection for EOR in the Mississippian oil reservoir. Seismic imaging pore fluid change in carbonate rocks is a challenging problem due to the stiff reservoir matrix masking the effects of fluid variability. However, previous work at Wellington field using pre-stack methods (AVO/AVAZ and impedance inversion) was able to map successfully porosity and fracture distribution in the Mississippian reservoir.

Background (baseline 3D) seismic data acquired in 2010 is compared to a 2D seismic line acquired in June 2016 over the CO_2 injection well KGS #2-32. The migration of CO_2 within the Mississippian is tracked in monitoring wells providing control points for the seismic analysis. Post-stack time-lapse seismic imaging proved not to be effective because of the difference in data quality between the post-injection 2D seismic line and the arbitrary line extracted from the pre-injection 3D baseline seismic. Imaging differences mask low impedance reservoir changes (modeled up to 6%) resulting from the estimated 25% CO_2 saturation.

Fluid substitution modeling is used to evaluate amplitude effects of CO_2 injection in the Mississippian reservoir (Adam et al., 2006; Misaghi et al., 2010; Vega et al., 2007). In spring 2016 the CO_2 injection in the Mississippian reservoir was completed. While spatial CO_2 saturation is difficult to predict from well control, and could be up to 50% in some areas, the average CO_2 saturation near the injection site was 25% and dissipated away from the injection well (Holubnyak, 2018, pers. comm). Fluid substitution models using 25%

CO_2 saturation were compared to original well logs for KGS #2-32. Well log data for Vp, Vs, and density were included in the models. The change in impedance over the reservoir interval (1114 – 1150 m) for these models showed a decrease in impedance of up to 6% with 25% CO_2 substitution and up to a 13% decrease with 50% CO_2 (Figure 1).

AVO analysis of the post-injection 2-D seismic line evaluated the amplitude response at seismic gathers near to and far from the injection well. The majority of the CDP's (including the injection well location KGS #2-32) exhibit significant scatter but an overall decrease in amplitude magnitude with offset is evident indicating a Class I AVO response (Figure 2). Noise identified in the gathers was suppressed using f-k filtering; however, intercept-gradient crossplots and gradient curves throughout the seismic line were too scattered to reliably identify changes in CO_2 saturation. Contributing factors are: 1) High matrix incompressibility of carbonate reservoirs make fluid detection challenging, 2) thin Mississippian reservoir thickness below seismic resolution, 3) a relatively small amount of CO_2 (20,000 tons) injected and 4) poor near surface conditions during data acquisition resulted in noisy seismic data. Although these challenges made it difficult to image the injected CO_2 in the field, fluid substitution modeling suggests a decrease in acoustic impedance with increasing CO_2 saturation, which may yield detectable changes in seismic data under favorable field conditions.

Key Findings

- Fluid substitution modeling indicates up to a 6% decrease in normal incidence acoustic impedance in the Mississippian reservoir with the presence of 25% CO_2 saturation and up to a 13% decrease in normal incidence acoustic impedance with 50% CO_2 saturation.
- Time-lapse evaluation of post-injection seismic reflection data show no amplitude anomalies associated with the CO_2 plume in the stacked (normal incidence) data. Poor data quality is noted.
- AVO analysis of field data is inconclusive due to poor data quality, low CO_2 volume injected, thin reservoir interval and incompressible matrix. Modeling predicts detectable amplitude response.

Deliverables

i) Comprehensive assessment of seismic methods (pre- and post-stack) for monitoring CO_2 injection in the Mississippian reservoir
ii) Development of seismic workflows for imaging pore-fluid changes and assessing EOR operations in the Mississippian
iii) MS Thesis, Haga L. (2019) Seismic Attribute Analysis and CO2 Monitoring within the Mississippian Reservoir, Wellington Field, Sumner County, Kansas

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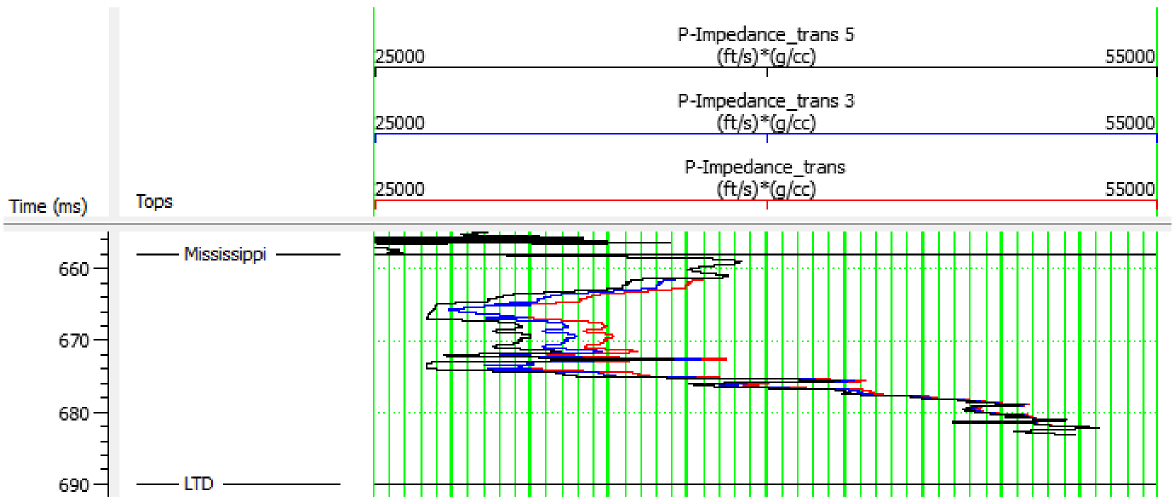

Figure 1. *Comparison of p-impedance curves of the original log (P-Impedance_trans - red) and the logs with 25% CO2 substitution (P-Impedance_trans3- blue) and 50% CO2 substitution (P-impedance_trans5 -5). Impedance decrease is observed with increasing CO2 saturation (Generated in Hampson Russell Suite).*

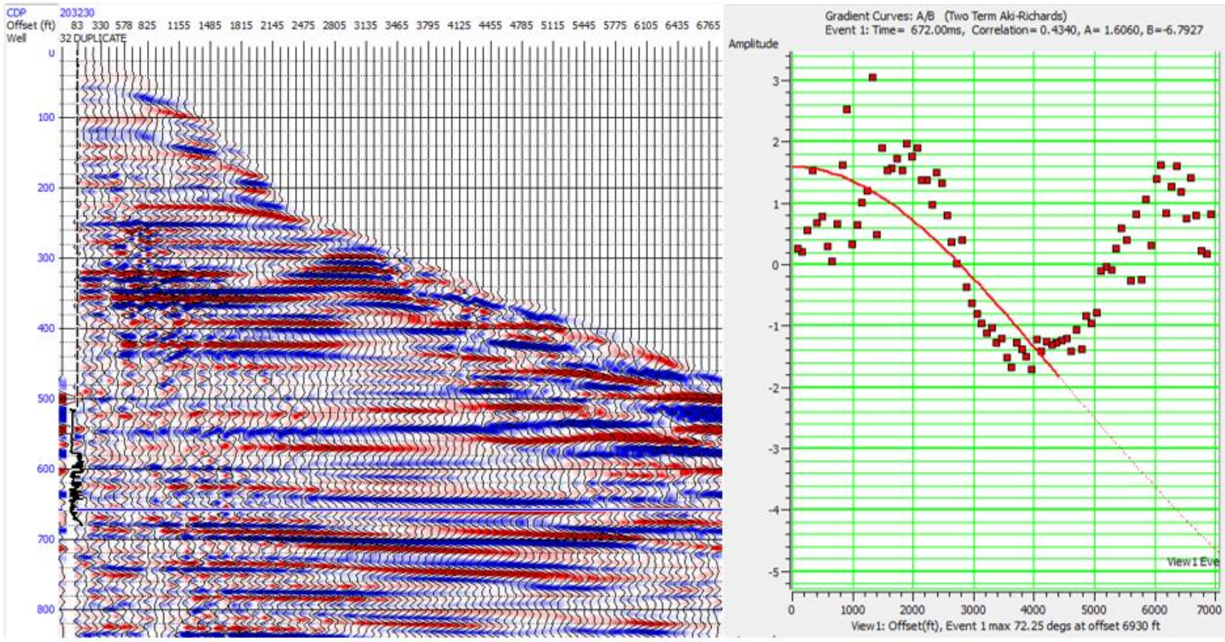

Figure 2. *Seismic gathers (left) and gradient curve (right) for CDP 203230 (location of the injection well). The gradient curve is displayed in the offset domain up to 7,000 feet (2,133.5 meters). The AVO data (red squares) is in general agreement to the modeled curve (red line) to approximately 4,000 feet or 1,219 meters. Post-critical reflections at offsets > 4000 ft result in anomalous amplitude response.*

Improving the Underlying Mechanisms of Low- and Modified- Salinity Water-Flooding Processes in Limestone Formations

Joel Tetteh and Reza Barati

SUBSURFACE APPLICATION: Lansing Kansas City limestone intervals, Oread and Foraker
STATUS: Long-term project in progress
TIMING: To be completed in the future if funded
FUNDING: Externally funded after being funded by KICC for 4 years

Purpose

The goal of this study is to investigate the effect of salinity modification on Lansing-Kansas City (LKC) limestone intervals via an investigation into the fluid mobilization and wettability alteration mechanisms using microfluidic devices and cryogenic-scanning electron microscopy (Cryo-SEM) technique.

Project Description

LKC reservoirs have been exposed to waterflooding for many years and have contributed to 47% of oil production within the State of Kansas (Evans and Newell, 2013). The potential of incremental oil recovery via reduced/modified salinity brine, low/modified salinity waterflooding (LMSW) in tertiary mode has been investigated in our lab using both Indiana and Lansing-Kansas City rocks (Tetteh et al., 2018, 2019, 2017; Tetteh and Barati, 2018). Some observations from this work includes:

- Sulfate ion was observed to reduce interfacial tension, enhance surface elasticity and suppress snap-off effect using seawater-like brine for waterflooding resulting in an improved oil recovery (Tetteh et al., 2017; Tetteh and Barati, 2018).
- Wettability alteration was observed and correlated to improved oil recovery when brine salinity was switched from high salinity formation water to seawater-like brine and finally to low salinity brines (Tetteh et al., 2018, 2019).
- Reduction in the electrostatic bond for both seawater and low salinity brines as well as the generation of repulsion force developed at the crude-oil-brine-rock interface using low salinity brines were attributing factors to the observed wettability alterations (Tetteh et al., 2019).

The possibility of applying low- and modified- salinity waterfloods in Kansas is enhanced due to the availability of such brines produced from some of the carbonate formations. This was explored in a work by Thompson (2018), where the possibility of produced water reuse through a brine exchange program was proposed to the inject low/modified salinity brine in LKC formation for enhance oil recovery purposes (Thompson, 2018). This would be economically and environmentally beneficial to the state of Kansas. However, a complete understanding of fluid mobilization and wettability alteration mechanisms is needed.

To further investigate into the fluid mobilization and the underlying mechanisms for the observed enhanced oil recovery using LMSW, a series of experimental procedures divided into three stages will be performed, i.e.: 1) microfluidic devices for fluid mobilization studies; 2) cryo-SEM for in-situ wettability studies; 3) coreflooding experiments and simulation; and 4) field simulation to investigate the applicability and feasibility of LMSW in LKC formations. The details are provided as follows:

- A pore network pattern for LKC and Indiana limestone rocks will be generated from thin section petrography images and it will be used in designing the microfluidic devices for fluid mobilization experiments.
- Microfluidic devices based on the generated pore network map will be prepared.
- The microfluidic device will be saturated and aged with LKC crude oil and flooding with high salinity, seawater-like and low salinity brines. The fluid movement and mobilization will be visualized using a microscope. This will provide an indication into mechanisms such as diffusion, osmosis and snap-off suppressions.
- Cryo-SEM images will be acquired on waterflooded (using high salinity, seawater-like and low salinity brines) limestone rock samples previously saturated and aged in LKC crude oil to keep fluid phase intact during the imaging stage.
- The acquired images will be processed using an image analysis software to investigate in-situ rock wettability and fluid mobilization the porous media.
- A simulation study of the lab experiments will be conducted to extract properties for the field scale modified waterflooding simulations. Data such as relative permeability and capillary pressure will be extracted from the various corefloods and the analyzed images.
- An inverted 5-spot pattern will be selected in a candidate reservoir in order to conduct a pilot test of low salinity waterflood and analyze the production and injection data in addition to the geochemistry of the pilot area.

Deliverables

This project will improve the understanding of wettability alteration and fluid mobilization in limestone rocks. This will improve reservoir simulation by capturing the active mechanism of LMSW in limestone rock for a better prediction of enhanced oil recovery.

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Polyelectrolyte and Nanoparticle Stabilized CO_2 Foams for Enhanced Oil Recovery

Reza Barati, Jyun-Syung Tsau and a student

SUBSURFACE APPLICATION: Mississippian limestone and Lansing Kansas City.
STATUS: Long-term project in progress
TIMING: To be completed in the future if funded
FUNDING: Not funded

Purpose

The overall objective of this project is to improve the stability of CO_2 foam systems, used for EOR purposes, using combinations of surfactants with polyelectrolytes and polyelectrolyte complex nanoparticles (PECNPs).

Project Description

Polyelectrolytes and their complexes can potentially reduce the dynamic movement of surfactants and prevent collapse of the formed lamellae. Moreover, polyelectrolytes have been found to reduce the critical micellar concentration of surfactants, thus potentially reducing the surfactant burden.

CO_2 foam has been used to overcome the aforementioned problems by dispersing CO_2 within a surfactant solution. CO_2 foams are agglomerations of gas bubbles separated from each other by liquid films with 60-95% gas content. Up to 100 times gas mobility reduction can be achieved using CO_2 foam via permeability reduction and viscosity enhancement [1]. Moreover, CO_2 foams are shear thinning fluids, and are considered an environmentally friendly material [1]. In addition to being complex systems, suffering from surfactant adsorption and poor injectivity, CO_2 foam is a thermodynamically unstable system [2]. Reportedly, lack of long-term stability, and stability in the presence of crude oil, has been a problem [3, 4]. Polyelectrolytes can potentially reduce the dynamic movement of surfactant [5, 6] and significantly strengthen the lamellae and making a more stable interface by interacting with surfactants of opposite charge, mainly through electrostatic forces.

Laboratory experiment will be conducted at reservoir pressure and temperature to find the most stable polyelectrolytes or PECNP systems with a nonionic surfactant to achieve foam durability and lower Interfacial Tension (IFT). A high pressure and high temperature (HPHT) view cell will be used to select the chemicals of the best performance with and without crude oil in the system. Our preliminary experiments have shown significant improvement in stability of CO_2 foam due to application of PECNPs (*Figure 1*). Effect of molecular weight and structure of polycations on effectiveness of stabilizing the foam and viscoelasticity of the interface will be studied by measuring IFT and foam column durability. A flow loop experiment will be used to examine the flow behavior of foam generated by the selected chemical systems under shear and its rheological properties. Finally, core flood experiments will be designed to demonstrate the improvement of oil recovery with the proposed chemical system and optimize the performance of polyelectrolyte and nanoparticle stabilized CO_2 foam for enhanced oil recovery (EOR) by measuring incremental oil recovery due to foam flooding and pressure drop along 10-inch cores (*Figure 2*). Foam flooding will be conducted in low salinity water and after low salinity waterflooding has left residual oil in the core.

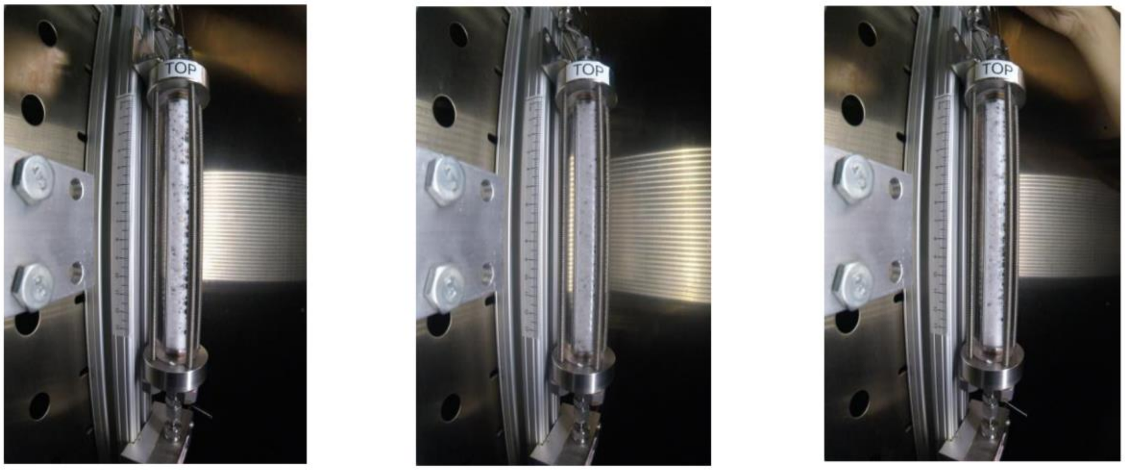

Figure 1. *Foams generated without crude oil with surfactant (left) surfactant-PEI (middle) and surfactant-NP (right) at 40 °C and 1300 psi.*

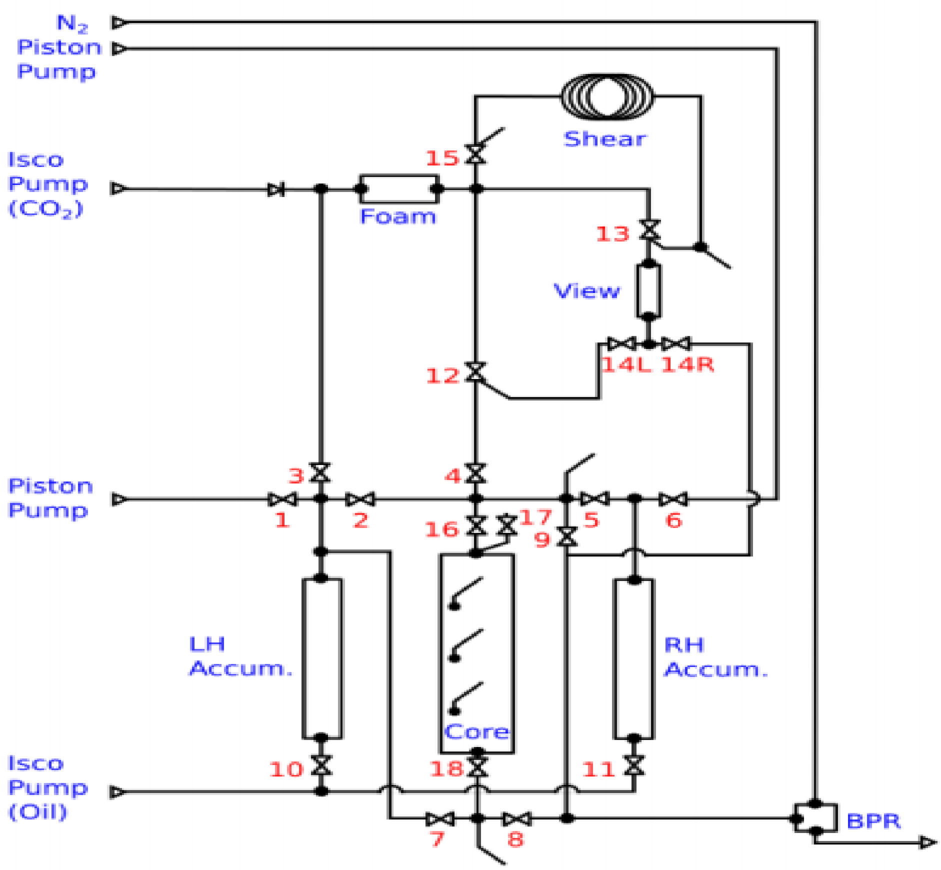

Figure 2. *Core flood system prepared for the injection of CO2-foam into a long core either 100% saturated with brine or brine at residual oil saturation.*

Deliverables

Successful completion of this project will provide a novel chemical system to improve mobility control for CO_2 application in EOR with stabilized foams. A surfactant-polyelectrolyte (s) system capable of generating stable CO_2-foam in the presence of crude oil, showing stable rheological properties under shear, and incremental crude oil and stable pressure drop across long cores is aimed to be the main deliverable of this research.

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Development of an Environmentally and Equipment Friendly Alternative for Matrix-Acidizing and Acid-Fracturing Applications

Reza Barati and students

SUBSURFACE APPLICATION: Mississippian limestone, Lansing Kansas City limestone intervals, Arbuckle, Austin Chalk, Eagle Ford, Buda limestone, Bakken, Niobrara
STATUS: Proposed project
TIMING: Preliminary results available; to be completed in the future if funded.
FUNDING: Seeking funding

Purpose

The overall objective of this project is to evaluate the performance of Ultraseries FF-01 (FF-01)as an environmentally- and equipment-friendly alternative for HCl that can be used for matrix acidizing and acid fracturing of wells producing from limestone formations. Specifically, this project will focus on developing this new product for the Mississippian Limestone Play (MLP) reservoirs in Kansas by evaluating the performance of FF01 as a single component product to be injected followed by evaluation of blends of FF01 and different polymers used in hydraulic fracturing of limestone formations.

Project Description

Well acidizing is one of the most common practices in the oil industry. Hydrochloric acid (HCl) has been used as the main acid for limestone stimulation purposes [1]. However, serious concerns regarding the health and safety of the field crew, corrosive nature of the acids for the tubular and equipment, environmental effects of the produced HCl, and rapid spending rate of HCl that prevents deep penetration into the formation has lead the industry towards a more environmentally and equipment friendly product [2]. FF01 is an environmentally- and equipment-friendly product of 101st Earthborn Environmental Technologies LP, which is a conversion to an organic carrier to maintain very low pH as a vehicle for aggressiveness, along with the creation of buffers and surface tension relievers for the effectiveness and safety [3]. Low pH, linear reaction with limestone, small amount of residue after reaction, longevity and higher viscosity than water with shear thinning behavior are the properties of this product.

The Mississippian Limestone Play (MLP) has become an important source of income for both Kansas and Oklahoma with hundreds of horizontal wells drilled and completed and millions of dollars of extra income [4, 5]. Acid treatment of oil wells with the purpose of increasing their productivity is a very common practice in the MLP. Considering the millions of barrels of fluids that are being used for acid treatments, use of a more environmentally- and equipment- friendly product will both save the companies money on their equipment and prevent the exposure of the acidizing crew and surface environment to HCl, both in liquid and vapor forms.

A complete lab study of this product including rheological, core-flooding and fracture conductivity tests at reservoir and ambient conditions will be followed by a matrix acidizing field test in a MLP production well.

During the research and development phase of this project:

- Rheological measurements will be conducted for FF01 and blends of FF01 with guar and hydrolized polyacrylamide (HPAM) products used for hydraulic fracturing of wells.
- HPHT reaction experiments will be conducted using a rotating disk setup and reaction parameters will be calculated by measuring the Ca concentration vs. time as a result of the acid reaction.
- Core-flooding experiments using different concentrations and blends of FF01 with each fracturing polymer as viscosifying agents and fracturing fluids will be conducted at reservoir conditions.
- Fracture conductivity measurements for fractures generated using the selected fluids will be conducted at reservoir conditions. Base cases will also be conducted using HCl for both ambient and reservoir conditions.

The final products most suitable for matrix acidizing and acid fracturing will be selected and the conditions of different wells owned by the producer will be studied to select a MLP well with the most appropriate conditions for matrix acidizing. The field test will be designed and conducted. Post-treatment data will be analyzed.

Deliverables

The deliverables are: 1) an optimized recipe and designed blends using acid alternatives and hydraulic fracturing polymers including a comparison of rheological properties (Figure 1), 2) Comparison of reaction parameters for commercial blends used in the industry with this novel environmentally-friendly product, 3) incremental permeability induced by matrix acidizing and acid fracturing using this new product (Figure 2) compared with HCl, and 4) improvement in the overall productivity due to acid fracturing using HCl alternatives.

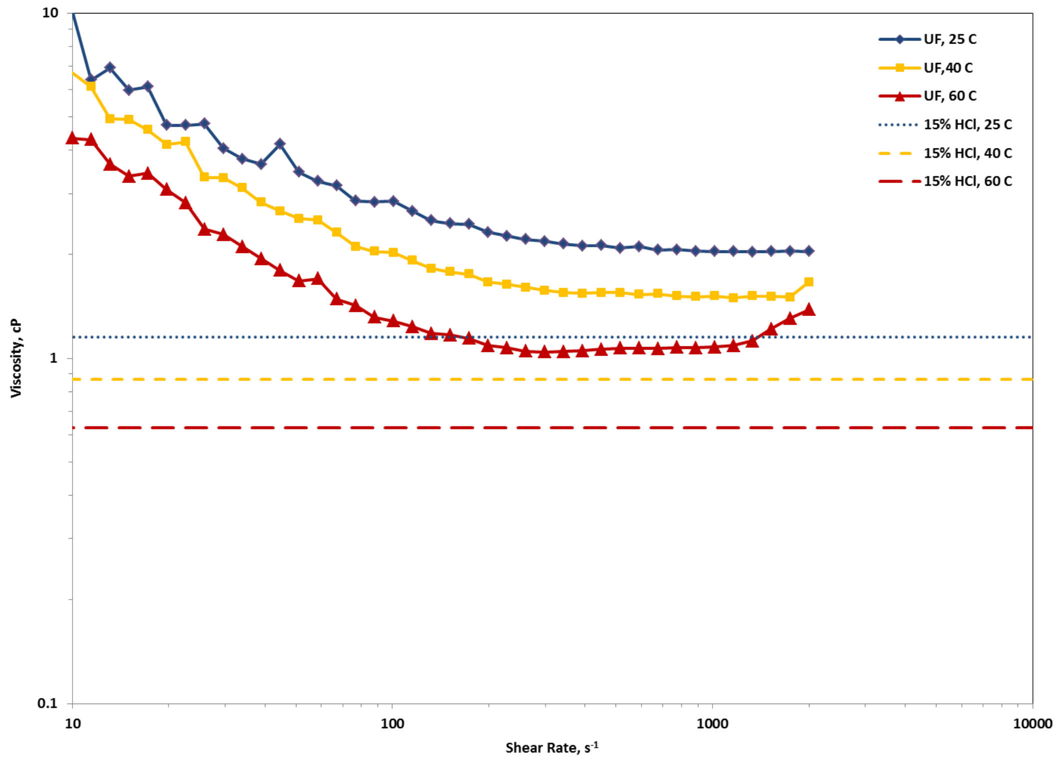

Figure 1. *Viscosity versus shear rate for FF-01 and 15% HCl at 25 °C, 40 °C, and 60 °C.*

Figure 2. *The LHS picture presents a core sample after a matrix acidizing experiment is performed. The RHS picture is a core sample after an acid fracturing experiment was performed.*

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Mechanistic Study of Low Salinity Waterflooding in Carbonate Reservoir Rocks - Pore-Scale Multi-Phase Reactive Transport Modeling

Siyan Liu, Chi Zhang and Reza Barati

SUBSURFACE APPLICATION: This study focuses on Lansing-Kansas City (LKC) group reservoirs, but it is broadly applicable to similar carbonate reservoirs such as the Smackover and Arab-D.
STATUS: *Proposed project*
TIMING: *Upon funding*
FUNDING: *None*

Purpose

Low salinity water injection (LSWI) is a promising technique for enhanced oil recovery (EOR) process in terms of the availability and affordability of the injectant, and the oil displacement efficiency (Tang and Morrow, 1999; Morrow and Buckley, 2011). In carbonate reservoir rocks, LSWI reports demonstrated significant percentages of increased oil production ranging from 7% - 16% (Yousef, et al., 2011; Puntervold, et al., 2018). Various underlying mechanisms are still under investigation and there is still no consensus on a single independent and dominant mechanism, especially in carbonate reservoirs. Additionally, experimental work shows that the incremental oil recovery will not always be attained (Seyyedi, et al., 2018: Zahid, et al., 2012; Ravari, 2011).

It is believed that the alternation of wettability during LSWI is a result of multiple interdependent mechanisms. The major mechanisms proposed are brine-oil interactions (Tetteh et al., 2018), multi-ion exchange and chemical reactions, wettability alterations, and electrical double layer (EDL) expansions (Sheng. 2014). The current body of literature about LSWI modeling and simulations is considering one or just a few mechanisms, due to the high level of complexity. We believe multiple factors should be considered in the modeling work for LSWI, and the objective of this work is to build a comprehensive pore-scale multi-component multi-phase reactive transport model for fundamental understanding of LSWI processes in carbonate reservoirs. The final goal is to use the model framework to optimize field-scale low salinity waterflooding applications.

Project Description

The comprehensive modeling approach is based on the hypothesis that multiphysics play an important role in the LSWI process, rather than focusing on only one or few physical/chemical behaviors, as no single process is independent. For example, complex interactions happen among chemical reactions, EDL expansions, brine-oil interactions, and all impact the oil/water wettability. Therefore, it is crucial to include multiple physical-chemical interactions within a dynamic system to realistically simulate the LSWI process.

In this project, the simulation will be conducted in a code coupling the advection-diffusion in porous media with chemical reactions. Lattice-Boltzmann method (LBM) code models the multi-component, multi-phase flow and diffusion and electrodynamics within the porous media. *PhreeqcRM*, from USGS, is the geochemical component. The major advantage of our modeling approach is the coupling scheme developed to leverage the capabilities of these two well-organized simulation frameworks. This allows us to build the well-structured pore-scale simulation framework with readily available extensibility for new physical/chemical models. The flexibility of the framework would allow for massive parallel computing, supported for large-scale simulations, to evolve to pore-scale modeling.

The LBM pseudo-component multi-phase Shan-Chen (SC) model (Shan and Chen, 1993), which currently uses static parameters to control the dynamic interfacial tension (IFT) and wettability, will be calibrated using experimental data. Ionic concentration distribution is obtained by solving Poisson-Nernst-Plank equations for diffusion and electro-kinetics after integrating fluid flow displacement. The geochemical solver *PhreeqcRM* will acquire the ionic concentrations for reaction calculations through an operator splitting approach, which includes equilibrium, kinetic, multi-ion exchange, and surface complexation reactions, as well as additional treatment for solid-fluid phase changes due to dissolution and precipitation. The evolution of porosity and permeability is evaluated during simulations. Updated concentrations and geometries are transferred back to the LBM solver for the next time step until the desired convergence is reached. Additional codes will be developed for work scheduling, pre-processing, post-processing and parameter optimization.

Deliverables

The deliverables of the project include the following parts:

1. A coupled simulation software framework: LBM flow and geochemical solver *PhreeqcRM* (Parkhurst and Wissmeier, 2015). Both of them are highly efficient C++ based code with Message Passing Interface (MPI) parallel computing features for large-scale simulations. *Palabos* is chosen for complex flow modeling in porous media with the capabilities of solving multi-phase flow and advection-diffusion problems *PhreeqcRM* is selected for solving various types of geochemical reactions during the LSWI.
2. This will be applied to a carbonate reservoir by using the LSWI model built with the simulation framework mentioned above. This comprehensive model will be calibrated from lab experimental data on the reservoir rock and be able to predict impacts from various factors during LSWI, such as the rock composition variations and composition of the injectant. After coupling with a 2D/3D flow model in micro-CT scanned rock images, the final model should provide guidance for optimizing LSWI EOR strategies on various real-world scenarios of carbonate reservoirs.

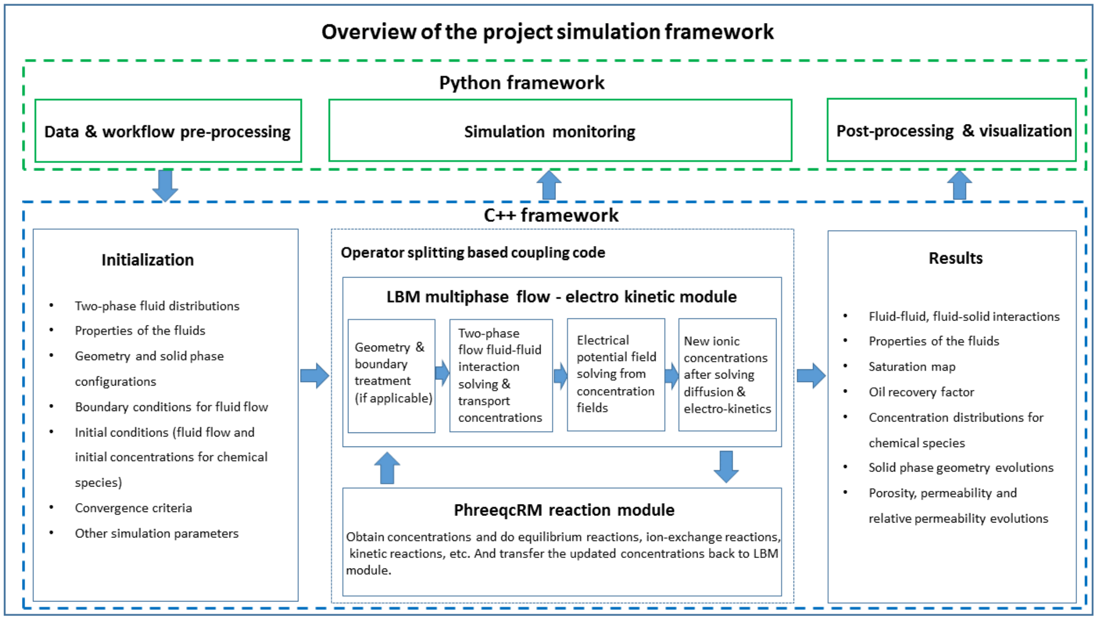

Figure 1. *Overview of the simulation framework*

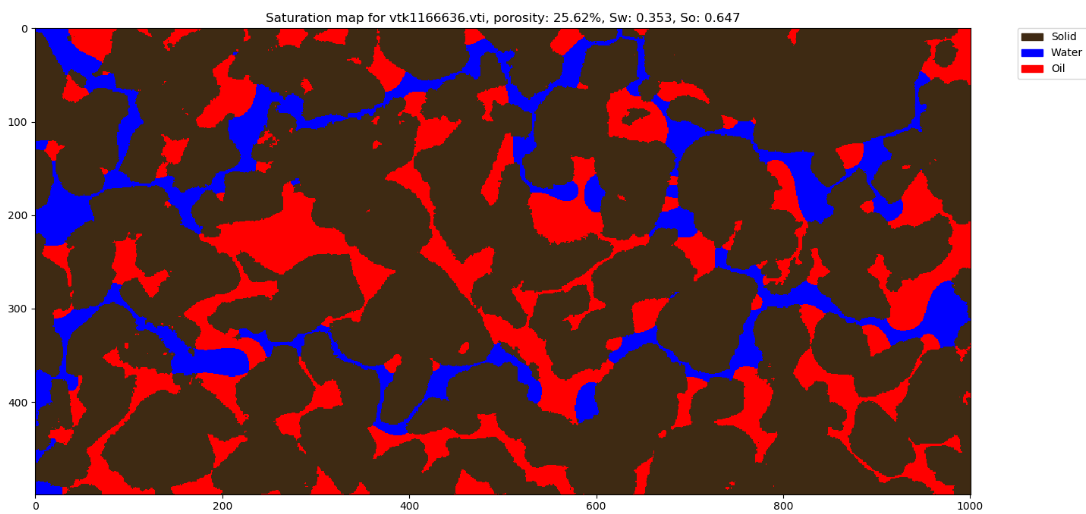

Figure 2. *2D 2-phase flow in porous media with Shan-Chen (SC) model for water displacing oil*

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An Integrated Workflow to Characterize Liquid Shale Candidates for Hydrocarbon Gas Huff-n-Puff

Sherifa Cudjoe, Jyun-Syung Tsau, Reza Barati and Robert Goldstein

SUBSURFACE APPLICATION: Eagle Ford, Bakken, Wolfcamp, Utica, Marcellus, Woodford, Permian, Haynesville, Niobrara shale plays, and international tight unconventional plays such as Vaca Muerta in Argentina.
STATUS: Focused-term project in progress
TIMING: Significant results to be reported
FUNDING: External Funding with partial funding from KICC

Purpose

The objectives of this work are: 1) characterize the microstructure of minerals and pores in Eagle Ford shale samples from different lithofacies using different imaging techniques; 2) study the effect of hydrocarbon gas on both soluble and insoluble organic matter (OM); and 3) generate representative pore network models (PNMs) of the different lithofacies and estimate bulk transport properties crucial for the design of gas huff-n-puff projects.

Project Description

Shale oil reservoirs are thought to be made up of the mineral matrix with isolated patches of organic matter, and are expected to possess very low matrix permeability. Recoverable oil production in shale oil formations is controlled by the rock (e.g., permeability) and the fluid properties (e.g., viscosity of the oil) as well as the natural reservoir drive energy, which tends to deplete rapidly. Thus, primary recovery in shale oil reservoirs with horizontal wells and multi-stage hydraulic fracturing for fluid flow is very low (5 – 10% of the original oil in place (OOIP)) [1]. Therefore, implementing improved/enhanced oil recovery (IOR/EOR) techniques such as gas huff-n-puff serves as a solution to maximize oil recovery. Recovery factors in the range of 20% - 80% have been reported in the literature for gas huff-n-puff recovery in shale oil reservoirs from numerical simulation, when contained within the stimulated reservoir volume (SRV) [2]. However, the interaction of organic matter (soluble/insoluble) with hydrocarbon gas at the pore-scale is not extensively studied as part of the huff-n-puff process. Furthermore, the complexity and heterogeneity of the shale reservoirs has given rise to pore-scale characterization, which involves the use of imaging techniques such as scanning electron microscopy (SEM) and focused ion beam – SEM (FIB-SEM), among others, to visualize and quantify rock properties through image analysis at the micrometer and nanometer scales. However, the current body of literature is missing a comprehensive study utilizing advanced imaging and analysis to investigate organic vs. inorganic tortuosity and its relation to the success of huff-n-puff injections in organic-rich, ultra-tight shale oil reservoirs.

SEM/BSE & EDS: High resolution SEM/BSE images will be acquired for the samples using a Hitachi 8230 instrument. It enables the visualization of internal minerals and pore systems of samples at a higher resolution. The Hitachi 8230 is connected to the silicon drift EDS detector (Oxford Instruments, X-Max^N, UK), which enables the identification of different elements within the regions of interest (ROIs) selected on the SEM/BSE images of the samples from which the mineral composition of the samples at the pore-scale can be inferred.

FIB-SEM and Digital Rock Analysis: The FEI Helios NanoFab 650 is used to acquire the FIB-SEM images of the shale samples. FIB-SEM is capable of resolving grains and nano-pores of organic-rich shales at ~ 5nm/ pixel by creating a series of 2D image slices on milled surfaces with thickness of ~10 nm. Subsequently, the series of 2D image slices will be reconstructed through digital rock analysis to obtain a 3D volume from which pore network models could be generated and bulk transport properties will be estimated.

Hydrocarbon Gas Huff-n-Puff: The original microstructure, mineral distribution, and composition of the samples will be thoroughly studied with SEM/BSE and EDS imaging techniques before the samples are exposed to hydrocarbon gas; their positions and orientations during SEM/BSE imaging will be fully documented in addition to mapping out key features of interest, presumed to be OM from EDS analysis. The shale samples will then be placed inside a huff-n-puff cell housed within a temperature controlled oven set at 125°C. Subsequently, the hydrocarbon gas will be injected at 3,500 psi to fill up the cell and allowed to soak for three (3) days.

Deliverables

A characterization workflow of the pore structure during huff-n-puff process is presented to optimize of the recovery for different scenarios of gas huff-n-puff. SEM/BSE and EDS will reveal the rock fabric of the samples and the various pore systems. Moreover, SEM/BSE & EDS analysis will support core-scale simulation of hydrocarbon gas huff-n-puff by demonstrating the gas-OM interaction. Pore network models will be extracted from FIB-SEM images to capture relevant pore structure of the samples and estimate bulk transport properties such as tortuosity and permeability.

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Experimental Investigation, Computer Simulation, and Field Application of CO_2 and Hydrocarbon Gas Huff-n-Puff in Unconventional Tight Carbonate Reservoirs

Qinwen-Fu, Jyun-Syung Tsau and Reza Barati

SUBSURFACE APPLICATION: Mississippian limestone, Eagle Ford, Austin Chalk, Wolfcamp, Bakken and Niobrara/Turner
STATUS: Project Proposed
TIMING: To be completed in the future if funded
FUNDING: Partially funded by Kansas Interdisciplinary Carbonate Consortium (KICC)

Purpose

The focus of this project will be on an experimental study of miscible, near miscible and immiscible huff-n-puff (HnP) injection tests in unconventional (tight) carbonate rocks. Specifically, the main objective of this project is to investigate the effect of diffusion during the HnP process. The experimental results will be matched with numerical simulation models of the HnP experiments in order to provide recommendations for EOR from liquid-rich unconventional rocks.

Project Description

New technologies in horizontal drilling and stimulation have assisted commercial production from unconventional oil reservoirs, but with a limited primary recovery factor of only 5-10% due to the fast decline in production rates caused by the ultra-low matrix permeability. The extra low permeability, high capillary forces, as well as possibility of clay swelling imposes risks to water or chemical flooding of these oil-bearing plays.

With the great extent of heterogeneity in unconventional shale oil reservoirs, complexity of any development plan is likely. Improved production from these tight formations will mostly rely upon development of an efficient technique. There is a growing body of evidence that suggests there is great potential for application of CO_2 and hydrocarbon gases to extract more oil from shale resources. Supercritical CO_2 is preferred compared to other gases because of its relatively high viscosity, high density and low miscibility pressure. Due to availability and their low prices, hydrocarbon gases are the most viable resource in these shale plays resulting in new developments around injection of such gaseous phases for EOR applications.

Several simulation studies have been reported for gas huff-n-puff in tight unconventional rocks. Extensive experimental studies or field-level experiments to evaluate the efficiency of the huff-n-puff injection in producing crude oil from tight or ultra-tight oil rocks is still missing. The overall objective of this project is to conduct a comprehensive study of the gas huff-n-puff injection method to improve recovery of tight oil reservoirs. Similar studies are applicable to other gas huff-n-puff cases.

This comprehensive experimental and simulation study will use core plugs placed in a setup capable of experimental simulation of the injection experiments. The results will be investigated first to improve the current understanding of the underlying mechanism(s) for recovery improvement using the huff-n-puff injection method. Moreover, comparison will be made between miscible versus immiscible injection of hydrocarbon gases.

Approaches

1) Drilled core plugs will be cleaned. Thin sections will also be prepared and analyzed at this stage to prepare a complete description of the rock system.

2) Oil samples will be collected from the well and oil properties, such as viscosity, density and composition of those samples will be measured. Minimum miscibility pressure will be measured using a swelling/extraction test. Equations of states will be developed at this stage.

3) Core plugs will be used for miscible and immiscible gas injection.

4) Core experiments will be simulated next to define effective diffusion coefficients.

5) Efficiency of the huff-n-puff method will be evaluated at this stage to improve understanding of the underlying mechanism(s).

6) Finally, pilot/field testing would be applied using the findings of the experimental work. Simulation of the post-treatment production results using a single-well model and history matching of the results in addition to comprehensive analyses of the collected data will provide sponsors with a thorough understanding of the underlying mechanism and applicability of the huff-n-puff methods for unconventional tight and ultra-tight oil reservoirs.

Deliverables

- Analyses of the huff-n-puff gas injection tests both experimentally and using simulations to understand the underlying mechanisms.
- Analyses of the treatment and post-treatment data including well and development area simulation scenarios.

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Multiphase Behavior during CO_2 EOR Processes in Carbonate Reservoirs

Laura Li and students

SUBSURFACE APPLICATION: Hall-Gurney reservoir in Kansas, Maljamar, Vacuum, and North Hobbs reservoirs in New Mexico, and Anton Irish, Levelland, Cedar lake reservoirs in Texas
STATUS: Project Proposed
TIMING: To be completed in the future if funded
FUNDING: None

Purpose
The objective of this project is to determine the multiphase behavior of reservoir fluids during CO_2 enhanced oil recovery (EOR) processes in carbonate reservoirs.

Project Description
Significance: Field tests in Kansas, Texas, New Mexico, and North Dakota have demonstrated that CO_2 injection is a successful EOR technique applicable to carbonate reservoirs (Manrique et al, 2007). In addition to the intensely heterogeneous porosity and permeability distribution, the phase behavior of reservoir fluids (i.e., water, oil, and CO_2) plays a significant role in the CO_2 EOR processes. Figure 1 presents a possible phase transition in the formation during the CO_2 injection (Okuno and Xu, 2014). Besides an oil-rich liquid phase (L_1) and a CO_2-rich vapor phase (V), an additional CO_2-rich liquid phase (L_2) may form under certain reservoir conditions. It means that the flow capacity of the L_1 and V phases need to be re-evaluated while an L_2 phase is present. The lack of a thorough understanding of such a complicated multiphase behavior greatly undermines the reliability of the CO_2 injection designs in either the laboratory or the fields. Hence, it is essential to clarify the multiphase behavior of reservoir fluids for achieving the maximum economic yield from CO_2 EOR projects in carbonate reservoirs.

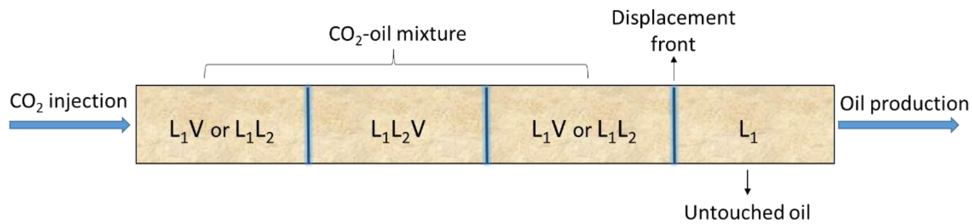


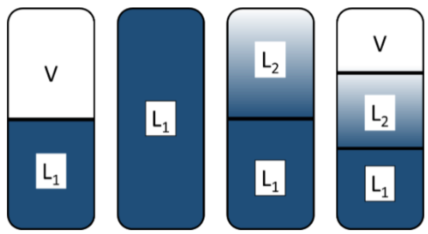
Figure 1. *Simulated phase transition in the formation during CO_2 injection*

Research Methodology: Theoretical investigations on the multiphase behavior of CO_2-oil systems preliminarily indicated that the L_2 phase at the reservoir conditions serves as a buffer between L_1 and V phases; however, no experimental proof demonstrating the effects of the L_2 phase is reported (Guler et al, 2001; Okuno et al., 2010). Therefore, this project is to comprehensively examine the multiphase behavior of CO2-oil systems by following two steps.

Step #1: Experimentally examine the multiphase behavior of CO_2-oil systems.

a. Considering the exclusiveness of oil properties in various reservoirs, oil samples will be collected from the targeted carbonate reservoir and used throughout all experiments. A full-visual pressure-volume-temperature (PVT) system with the pressure up to 700 bar, the temperature up to 200 ºC, and the capacity of 300 ml will be employed to measure and visually observe the complex multiphase behavior.

b. The multiphase behavior of the CO_2-oil system will be measured through four scenarios (see Figure 2), i.e., L_1V two-phase, L_1 single-phase, L_1L_2 two-phase, and L_1L_2V three-phase experiments. The comparison of the four scenarios will explicitly reveal the effect of the L_2 phase on the phase behavior of the CO_2-oil system.



(a) (b) (c) (d)

Figure 2. *Four scenarios: (a) L_1V two-phase; (b) L_1 single-phase; (c) L_1L_2 two-phase; and (d) L_1L_2V three-phase.*

c. The phase boundaries together with the swelling factors will be measured for each individual scenario. Subsequently, both the *P-T* and *P-x(composition)* phase diagrams will be achieved to analyze the phase changes during the CO_2 EOR processes in carbonate reservoirs.

Step #2: Develop an improved and practical phase behavior model for the CO_2-oil system.

According to experimental measurements, an improved and practical phase behavior model will be developed by modifying the cubic equation of state models. The effects of the L_2 phase on the phase behavior of the CO_2-oil system will be embodied in the developed model, which provide a convenient and reliable means for engineers to evaluate the fluid properties in the CO_2 EOR processes.

Deliverables

Multiphase behavior diagrams of the CO_2-oil system will be developed to deliver significant insights into the phase changes in the CO_2 EOR processes. Also, the newly developed phase behavior model will be provided for engineers to optimize the CO_2 EOR design at both lab- and field-scale. A successful outcome will improve the reliability of the CO_2-EOR simulation by using more accurate fluid properties.

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A User-Friendly Package to Determine Wormhole Propagation During Matrix Acidizing

Zhaoqi Fan and Laura Li

SUBSURFACE APPLICATION: Mississippian limestone in Kansas and Oklahoma, Arbuckle, Grayburg/ San Andres of Permian Basin, Smackover, and Arab
STATUS: Project Proposed
TIMING: To be completed in the future if funded
FUNDING: None

Purpose

The objective of this project is to develop a user-friendly package for engineers to evaluate the wormhole propagation after the acidizing of carbonates under various conditions.

Project Description

Background: The matrix acidizing has been extensively used to stimulate the production from carbonate reservoirs due to the formation of high-permeability conductive channels. Considering the capacity and injection rate of acids, the high-permeability channel may form a face dissolution, conical wormhole, dominant wormhole, ramified wormhole, or uniform dissolution in a carbonate formation (Buijse and Glasbergen, 2005). Since the dominant wormhole is the most effective means of matrix stimulation, numerous efforts have been made to optimize the injection rate that forms the dominant wormholes with minimized acid volume (Fredd and Fogler, 1999). However, the quantitative description of the dominant wormhole geometry and trajectory is still a challenge due to the complex flow conditions in the acidizing process.

State-of-the-art wormhole characterization & limitations: The wormhole geometry and trajectory are mainly collected from the observations in the laboratory by using neutron radiography, CT scan, and NMR (Zakaria et al, 2015). However, it is difficult to quantitatively predict the wormhole propagation in fields based on the measured wormholes in the laboratory due to the strong heterogeneity. Theoretically, semi-empirical models and continuum models have been developed to represent the dynamic wormhole propagation by considering axial convection, fluid loss, transverse diffusion, and chemical reaction on the surface (Daccord et al, 1993; Buijse and Glasbergen, 2005; Kalia and Balakotaiah, 2009). In practice, the semi-empirical models only provide an average estimate of the wormhole growth rate. Although the continuum models usually depict a comprehensive picture of wormholes, the unaffordable computational cost is usually induced for field-scale wormhole characterization due to the strong nonlinearity of continuum models.

Research plan: The formation of wormholes is a consequence of competence between the acid-rock reaction responsible for the pore growth and transport mechanisms that account for the direction of the acid penetration. It is indicated that more acid is attracted by high permeability regions and pore distribution can be used as a critical parameter to predict the wormhole propagation direction (Dong et al. 2017; Panga et al. 2005). Therefore, the wormhole propagation in formations is represented, in this project, by a one-dimensional wormhole growth process and a wormhole propagation direction determination process, which would greatly improve the efficiency and applicability of the aforementioned continuum models.

To be specific, this project includes:

Task 1: Develop a one-dimensional continuum model by considering the convection, diffusion, chemical reaction, and fluid loss in acidizing processes. The increase of the wormhole radius and length will be quantitatively determined by using the developed acidizing model.

***Task 2*:** Propose a criterion to govern wormhole propagation direction. The heterogeneity and Darcy's law will be considered to derive such a criterion. The integration of the one-dimensional continuum model and the criterion compose a wormhole growth model and provide a full description of the wormhole propagation under various conditions.

***Task 3*:** Validate the wormhole growth model against laboratory acidizing experiments. In addition, an ensemble-based algorithm is to be incorporated with the wormhole growth model for analyzing the uncertainties associated with the evaluated wormhole propagation.

***Task 4*:** Develop a user-friendly package by encapsulating the aforementioned models.

Deliverables

A user-friendly package will be developed to evaluate the wormhole propagation under various acidizing conditions and then provide valuable feedbacks to matrix acidizing design at both the lab- and field-scale. In addition, such a package is adaptive to various simulators, which furnishes a means of synergistic optimization of acidizing and productivity in carbonate reservoirs.

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Microbial Enhancement of In Situ CO_2 Sequestration

Jennifer Roberts and David Fowle

SUBSURFACE APPLICATION: Applicable to Mississippi Lime; Arbuckle Aquifer and other reservoirs targeted for tertiary recovery via CO_2 injection or aquifers targeted for CO_2 storage.
STATUS: Project Proposed
TIMING: To be completed in the future if recommended by membership, funded, or staffed
FUNDING: None

Purpose

In recent years there has been significant advancements investigating aquifers, mine tailings, and oil fields as a long-term storage solution for carbon dioxide. One potential fate for injected CO_2 is sequestration of CO_2 into sparingly soluble carbonate minerals. Whereas microorganisms are known to facilitate precipitation of carbonate minerals, it remains unclear whether they promote carbonate precipitation in CO_2-injected reservoir systems. Here we will investigate: 1) the extent that microorganisms and other functionalized particles influence carbonate precipitation under reservoir temperatures and pressures in the presence of super critical CO_2 and high partial pressures of CO_2, and; 2) strategies to enhance precipitation kinetics through stimulation of *in situ* native microbial communities or injection of natural or engineered materials.

Project Description

The introduction of high partial pressures of CO_2 into the subsurface will influence mineral solubility. The dissolution and precipitation of mineral phases will lead to changes in reservoir permeability, and the potential sequestration of CO_2 into insoluble carbonate minerals. These abiotic processes have been investigated at the bench (e.g., HANSEN, et al., 2005) and field scale (e.g., KHARAKA et al., 2006) yet influences on these processes by native microorganisms and other charged surfaces remain unclear. Because microorganisms have been shown to be integral to carbonate mineral formation in some environments (Figure 1), in this study we will develop strategies to enhance carbonate mineral precipitation under reservoir conditions. We hypothesize that:

- Microbial activity and reactive surfaces can enhance rates of carbonate mineral precipitation; and
- By distinguishing the mechanism of precipitation, we can engineer protocols to enhance these processes *in situ*.

These hypotheses will be tested using controlled laboratory batch experiments containing native consortia from reservoir fluids. We will characterize precipitation of carbonate phases as a function of solution chemistry and the presence/absence of cells; and characterize precipitation of carbonate phases as a function of solution chemistry and active metabolic pathways.

Deliverables

We expect precipitation of carbonate phases will be facilitated by both metabolic activity and cell wall interactions. By characterizing the abundance and types of microorganisms in a specific system we can produce better estimates of sequestration and devise approaches to enhance sequestration. Specific deliverables include: 1) quantitative data to assess the rate of carbonate precipitation under reservoir conditions as a function of biomass; 2) implementation of experimental data in conjunction with site specific characterization of microbial populations into predictive models; and 3) engineered approaches for enhancing carbonate precipitation *in situ* including enhancement of carbonate-precipitating metabolic activities or bioaugmentation.

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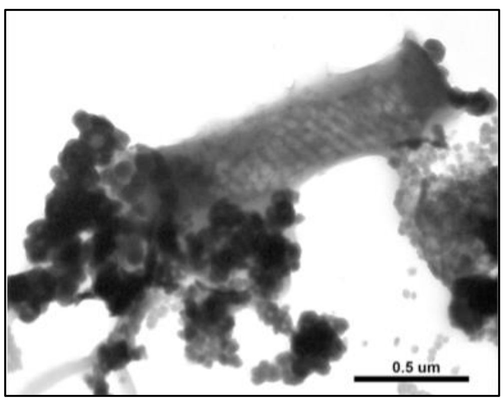

Figure 1. *TEM photomicrograph of a microbial surface coated in carbonate precipitate.*

CO_2 Flooding to Improve Oil Recovery in Carbonate Reservoirs

Jyun-Syung Tsau, Graduate student

SUBSURFACE APPLICATION: Arbuckle reservoirs in Kansas or other similar type of reservoirs with operation pressure below minimum miscibility pressure
STATUS: Long-term project
TIMING: Significant results to be reported – Results currently available to membership
FUNDING: None

Purpose

Carbon dioxide (CO_2) injection for enhanced oil recovery is a proven technology. It is also considered as one of the most promising methods for carbon sequestration in geologic formations. CO_2 injections are normally operated at a pressure above the minimum miscibility pressure (MMP), which is determined by crude oil composition and reservoir conditions. However, many reservoirs in the United States and around the world are at shallow depths or geologic conditions exist such that they operate at pressures below the MMP. When CO_2 injection operates at a pressure below the MMP, displacement efficiency decreases as a result of the loss of miscibility but is still better than that in a waterflooding process. This better recovery has been attributed to possible improvement of the mobility ratio displacement and an extraction process, which are all closely related to operating pressure. To increase the resource base for CO_2 flooding and substantially increase the production from reservoirs, there is a need to characterize the near miscible conditions of reservoirs and investigate the feasibility of CO_2 displacements at near miscible pressures by conducting appropriate experimental work and reservoir simulation.

Project Description

Arbuckle reservoirs historically have been viewed as fracture-controlled karstic reservoirs with porosity and permeability influenced by basement structural patterns and subaerial exposure. These reservoirs have produced an estimated 2.2 billion barrels of oil representing 35% of the 6.1 billion barrels of oil of total Kansas oil production and are a significant resource in Kansas for improved oil recovery. Initial studies of CO_2 miscible flooding indicated that miscibility is not achievable at the reservoir operating pressure in most Arbuckle reservoirs. On the other hand, if the reservoir operating pressure is above the MMP, CO_2 miscible process can be considered to improve the oil recovery. An example of such a reservoir is located at a depth of about 2900 feet in Hall Gurney Field, Russell County, Kansas.

The objective of this project is to investigate the feasibility of applying CO_2 displacement at miscible or near miscible pressure to increase the resource base for CO_2 flooding and substantially increase the production from these reservoirs. The proposed work includes experimental and simulation studies. The experimental study will 1) systematically characterize the miscible and near miscible condition and study recovery of waterflood residual oil using CO_2 displacement at near miscible pressure, and 2) identify key parameters in phase behavior and flow tests for simulation modeling. The simulation study will develop a representative model to simulate miscible and near miscible displacement physics and 2) assess the potential of recovery processes at miscible and near miscible pressures.

Deliverables

The project will develop a methodology to design field application of carbon dioxide injection at near miscible and miscible condition. Economics of pilot/demonstration and field application on carbonate reservoirs of interest will be evaluated.

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Carbonated Water Injection to Improve Oil Recovery in Carbonate Reservoirs

Jyun-Syung Tsau, Graduate student

SUBSURFACE APPLICATION: Kansas carbonate reservoirs such as Arbuckle, Lansing Kansas City and Mississippian formation
STATUS: Long-term project
TIMING: not yet available to membership
FUNDING: None

Purpose
Carbonated water injection (CWI) is a promising alternative of conventional CO_2 flooding, requiring less amount of CO_2, to improve oil recovery. The solubility of CO_2 in water is high as compared to other gases commonly used in gas injection process. During the CWI, the dissolved CO_2 transferred from the injected water to the oil phase increases the oil mobility as a result of oil viscosity reduction and swelling. However, the solubility of CO_2 depends on reservoir temperature, pressure and water salinity. Many carbonate reservoirs in Kansas produced a large amount of water with high salinity either under water flooding or through the natural water drive by aquifer. It is challenging to dispose huge amounts of water associated with such a field operation. As a result, utilizing the produced water with enrichment of CO_2 as a displacing agent is proposed to improve oil recovery (IOR) in these carbonate reservoirs.

Project Description
Arbuckle reservoirs have produced an estimated 2.2 billion barrels of oil representing 35% of the 6.1 billion barrels of oil of total Kansas oil production. Lansing Kansas City (LKC) group is the second largest unit in Kansas with over one billion barrel recovered to date. It accounts for 19% of Kansas total oil produced each year. Since 1970, 12% of state's total oil production also came from Mississippian formations. All these carbonate reservoirs remain a significant resource in Kansas for improved oil recovery. CO_2 miscible and near miscible process has been considered to improve the oil recovery in these reservoirs at Hall Gurney Field, Russell County and Ogallah Unit, Trego County, Kansas. However, due to the lack of CO2 source nearby, commercial filed application has not been implemented.

The objective of this project is to investigate the feasibility of applying CWI as an alternative to conventional CO_2 flood for improving oil recovery on these carbonate reservoirs. The proposed work includes experimental and simulation studies. The experimental study will 1) systematically characterize the IOR mechanisms of CWI which include partition of CO_2 in water/oil phase, dynamic wettability alternation of carbonate, carbonate dissolution and deposition due to the presence of CO_2 in water, and 2) identify key parameters of interaction between fluid/fluid and fluid/rock for simulation modeling. The simulation study will develop a representative model to simulate laboratory core flooding experiment, and 2) assess the potential of recovery processes at a field scale.

Deliverables

The project will develop a methodology to design and conduct laboratory experiment and future field application of carbonate water injection. Economics of pilot/demonstration and field application on carbonate reservoirs of interest will be evaluated.

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