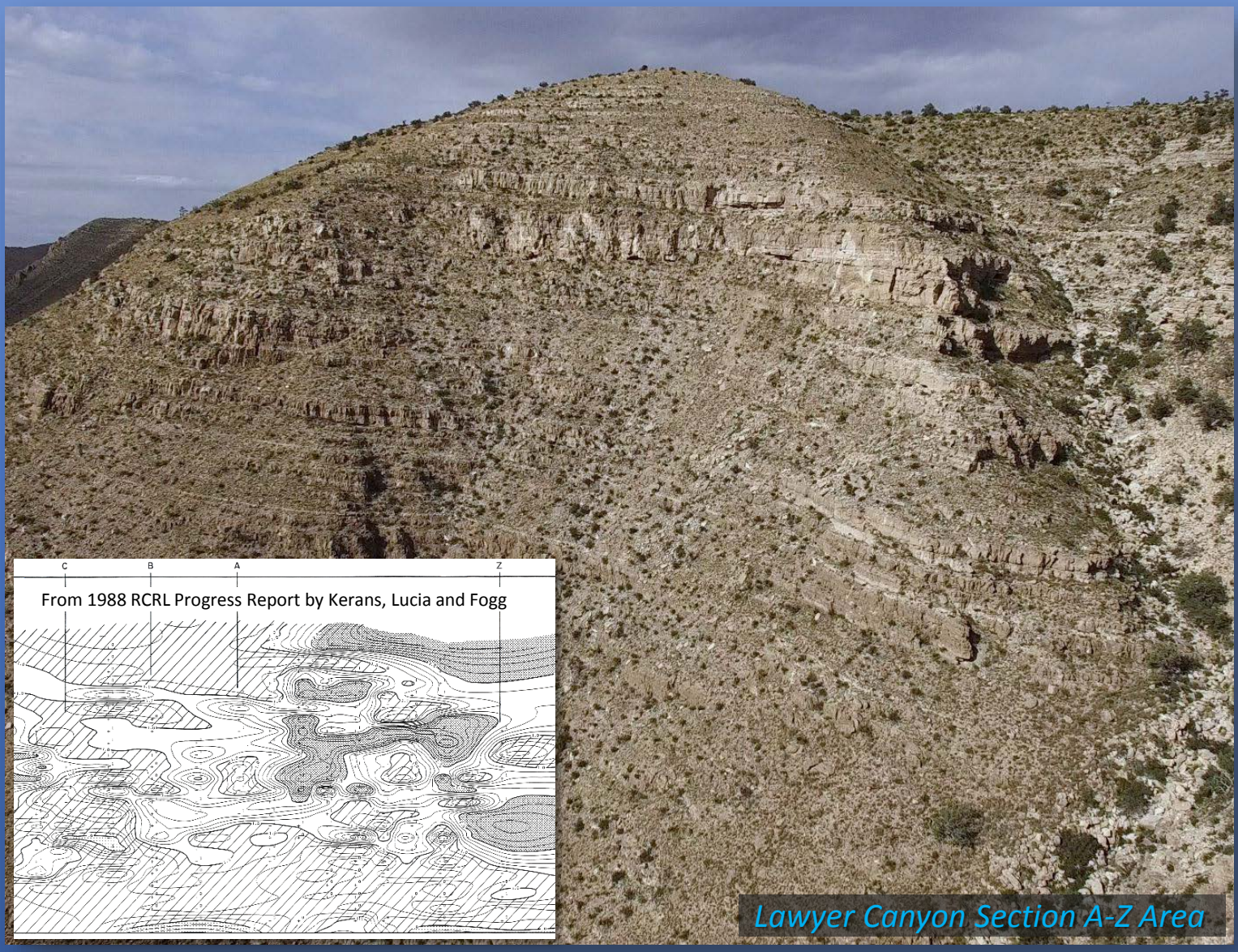
Reservoir Characterization Research Laboratory

Executive Summary and Prospectus for 2017

Charles Kerans and Robert Loucks
Co-Principal Investigators



Lawyer Canyon Section A-Z Area

TEXAS Geosciences
Bureau of Economic Geology
Jackson School of Geosciences
The University of Texas at Austin

Bureau of Economic Geology
Scott W. Tinker, Director
The University of Texas at Austin
Austin, Texas 78713-8924

Reservoir Characterization Research Laboratory

Research Plans for 2017

Outcrop and Subsurface Characterization of Carbonate Reservoirs for Improved Recovery of Remaining Hydrocarbons

Charles Kerans[1, 2] and Robert Loucks[1]

Co-Principal Investigators

Research Staff

Xavier Janson

Josh Lambert

Christopher Zahm

[1]Bureau of Economic Geology – Scott W. Tinker, Director

[2]Department of Geological Sciences

Jackson School of Geosciences

The University of Texas at Austin

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Outcrop and Subsurface Characterization of Carbonate Reservoirs for Improved Recovery of Remaining Hydrocarbons

EXECUTIVE SUMMARY

The Reservoir Characterization Research Laboratory (RCRL) for carbonate studies is an industrial research consortium run by the Bureau of Economic Geology (BEG) and the Department of Geological Sciences, Jackson School of Geosciences, at The University of Texas at Austin (UT). RCRL's mission is to use outcrop and subsurface geologic, geophysical, and petrophysical data from carbonate reservoir strata as the basis for developing new and integrated methodologies and concepts to better explain and describe the 3D reservoir environment and improve hydrocarbon recovery factors. In addition to this research mission, RCRL is dedicated to technology transfer and education, and consistently offers state-of-the-art training in the form of short courses, field seminars, in-house reviews of selected assets, and extensive graduate student supervision and guided research. In 2017, the RCRL research will broadly be organized around the three following research directions: (1) Early Permian shelf-to-basin syntectonic to early post-tectonic stratigraphy of the in the Delaware and Midland Basins; (2) Gulf of Mexico carbonate reservoir settings, pore systems, fracture character, and margin variability; and (3) Cenozoic carbonate platforms and high-resolution stratigraphy and diagenesis of icehouse isolated platforms. Within these themes, specific projects will focus on various scale of carbonate reservoir characterization ranging from the platform-wide features to reservoir micropores.

FUNDING

We invite your company to participate in the continuation of the RCRL Carbonate Reservoirs Research Program for 2017. A list of recent sponsors is presented in Table 1. In 2017, the annual RCRL Industrial Associates contribution to the program will continue to be $55,000 per year. To encourage sponsors to commit to a 2-year agreement so that we can better plan a longer-range research program and reduce the time and effort in securing agreements, we offer a 2-year (2017 and 2018) rate of $50,000 per year. The agreement would be such that a Memorandum of

Agreement (MOA) would be signed agreeing to a 2-year commitment, and payment would be due at the beginning of each year.

RCRL PROGRAM

The RCRL program has existed continuously since 1987, maintaining strong company sponsorship each year. In 2016, 21 companies supported RCRL research (Table 1).

Anadarko	Devon	Petrochina	Statoil
Apache	Ecopetrol	Pioneer	Wintershall
BG Group	Husky	Repsol	University Texas Lands
BHP	Ion	Saudi Aramco	
Cenovus	JAPEX	Shell	
Chevron	OXY	Sinopec	

Table 1. 2016 RCRL Sponsors

Principal Staff

Dr. Charles Kerans, Goldhammer Chair of Carbonate Geology, DGS, Principal Investigator
Dr. Robert Loucks, Senior Research Scientist, Principal Investigator
Dr. Xavier Janson, Research Scientist, Geologist
Dr. Christopher Zahm, Research Scientist Associate V, Geologist
Mr. Donald Brooks, Rock Mechanics Technician
Mr. Josh Lambert, Research Scientist Associate I
Ms. Stephaine Lane, Project Coordinator

Associate Staff

Dr. Sheng Peng, Research Associate, Geologist
Dr. Steve Ruppel, Senior Research Scientist, Geologist
Dr. Hongliu Zeng, Senior Research Scientist, Geophysicist
Dr. Carla Sanchez-Phelps, Research Fellow, Geologist/geophysicist
Mr. Evan Sivil, Research Technician, Geochemistry

Staff members have had extensive industry experience or have worked closely with industry, and they are continually striving to be familiar with the challenges and questions facing development geoscientists and engineers. We are also proud of our graduate students (Appendix A) associated with RCRL, which include several award-winning students. Most of our graduated students are now working in industry research, production and exploration roles.

2017 RESEARCH INTERESTS

The RCRL group has unique expertise that addresses various research questions in carbonate shelf to basin systems and at scale of investigation from nanopores to basin architecture. In 2017, RCRL research will broadly be organized around the three following research directions: (1) Early Permian shelf-to-basin synorogenic to early post-orogenic stratigraphy of the Delaware and Midland Basins; (2) Gulf of Mexico carbonate reservoir settings, pore systems, fracture character, and margin variability; and (3) Cenozoic carbonate platforms and high-resolution stratigraphy and diagenesis of icehouse isolated platforms. Within those themes, specific projects will focus on various aspect and scale of carbonate reservoir characterization. The RCRL Group approaches reservoir characterization through four main scales of investigation: (1) platform-to-basin scale stratigraphy; (2) reservoir architecture, including both matrix and nonmatrix systems (e.g., fractures and paleokarst); (3) structural and geomechanical properties characterization; and (4) pore networks and their reservoir distribution. Research questions for each theme are developed using both subsurface data and outcrop analogs. We emphasize quantifying what we observe so that our research is applicable to reservoir models and valuable in providing predictive relationships and conceptual tools for reservoir characterization and play analysis. Our research focus areas, themes, and topics have been developed out of our experience and feedback from our sponsorship.

INFORMATION TRANSFER

Our industrial sponsors receive research results at annual review meetings, in short courses, during mentoring activities, in publications, and on our continually updated, members-only RCRL website database (http://www.beg.utexas.edu/rcrl/ members/). This online searchable website allows us to protect your investment in our collective research and makes previously presented material easy to locate and download from anywhere in the world. Each paying member company is given login information to the 'members only' portion of our website. This data area contains digital presentations, including archived video and annotated presentations, developed maps, core photos, porosity and permeability data, digital-outcrop reservoir models, core workshop guidebooks, and field-trip guidebooks from past and current RCRL field trips.

Workshops and Field Seminar

In addition to the Annual Review Meeting with the associated Field Trip and Core Workshop, we will be offering a training workshop in spring 2017 in Austin. The workshops are interactive and utilize subsurface data, including seismic, wireline logs and core, along with applicable outcrop analogs to emphasize applications of key elements that have been developed by RCRL over the

past three decades. In spring 2016 we conducted a week-long series of one-day, standalone courses that included (1) introduction to carbonates and principles of carbonate exploration and exploitation, (2) seismic characterization of carbonate systems, (3) integrated core, log, and seismic analysis for construction of high-resolution sequence frameworks for reservoir characterization and modeling, (4) principles of carbonate karst and associated reservoirs, and (5) 3D fracture modeling using carbonate rock properties and mechanical stratigraphy. We intend to run the workshop or short course during the second week of May, 2017. Topics for the workshop or short course will be determined by the interests of the sponsor companies, which will be solicited before the end of 2016. Member companies are encouraged to send staff or teams for one, several, or all of the modules covered in the short course as there is no enrollment fee.

Sponsor Interactions with RCRL Staff

RCRL makes a concerted effort to interact with sponsors during the year through company-specific discussions and short-term projects to help transfer research results into their exploration and production workflow. Over the last several years, RCRL researchers have visited numerous U.S. domestic and international companies. In the past year we have traveled to companies or hosted groups in Austin.

If your company has an interest in developing a cooperative project with members of the RCRL staff, we would like to hear from you. These cooperative projects, in which RCRL and company staff learn together through hands-on data analysis of current production/exploration challenges, are essential to maintenance of the real-world relevance of our group. In addition, access to data that can be worked on, as well as presented, is imperative.

RCRL Graduate Student Mentoring and Thesis Supervision

RCRL has produced a significant number of graduates with advanced degrees in carbonates that are now working in industry. Charles Kerans, a professor and the Chairman of the Department of Geological Sciences, Jackson School of Geosciences, holds the Robert K. Goldhammer Chair in Carbonate Geology. He teaches both undergraduate and graduate carbonates courses and this gives RCRL a unique ability to have students interacting with RCRL scientists and researchers while they obtain their degree. Xavier Janson, Jerry Lucia, Chris Zahm, Steve Ruppel, and Bob Loucks all teach or have taught courses in the Jackson School, and several are on the Graduate Studies Committee. Students obtain comprehensive training in carbonate systems working on RCRL projects and interacting with RCRL professional staff. Each student presents his or her work at the Annual Review Meeting, which is an opportunity for sponsors to get to know students and consider them for possible future employment. A list of recent and active students is presented in Appendix A.

RESEARCH PROGRAM FOR 2017

INTRODUCTION

A hallmark of the RCRL research program is its unique combination of recognizing subsurface characterization challenges that can be improved by the use of well-defined outcrop analogs and a breadth of subsurface characterization experience that is brought to bear on problems important to sponsors of the program. In the 30 years of RCRL research on carbonate systems, technical methods have been developed that populate the sequence stratigraphic framework with reservoir-flow properties so as to improve hydrocarbon recovery. Yet many challenges still exist within carbonate reservoirs, especially in the area of integration of nonmatrix pore systems (e.g., fractures and karst), pore-network-related diagenesis (e.g., micropores in tight carbonate reservoirs), and the realistic three-dimensional variability of lithofacies distribution. We think that the research challenges that remain have the best chance of being solved when they are incorporated into the overarching stratigraphic architecture that provides the fundamental framework of the reservoir characterization process.

Research questions and anticipated products for each theme are developed using both subsurface data and outcrop analogs. Our research-focus areas, themes, and topics have been developed out of our experience and feedback from our sponsorship.

A presentation of our 2017 Research Program can be found on our publicly available website: http://www.beg.utexas.edu/rcrl/.

Key Research Areas for 2017

In 2017, the RCRL research will broadly be organized around the three following research directions: (1) Early Permian shelf-to-basin synorogenic to early post-orogenic stratigraphy of the Delaware and Midland Basins; (2) Gulf of Mexico carbonate reservoir settings, pore systems, fracture character, and margin variability; and (3) Cenozoic carbonate platforms and high-resolution stratigraphy and diagenesis of icehouse isolated platforms. Within these three areas, specific projects will focus on a variety of aspects and scale of carbonate reservoir characterization. The RCRL Group approaches reservoir characterization through four main scales of investigation: (1) platform-to-basin scale stratigraphy; (2) reservoir architecture, including both matrix and nonmatrix systems (e.g., fractures and paleokarst); (3) structural and geomechanical properties characterization; and (4) pore networks and their reservoir distribution. Each key area is highlighted below with a brief description of the research efforts the RCRL group will be focused on for 2017.

<u>Research Area 1</u> Early Permian Shelf-to-Basin Synorogenic to Early Post-Orogenic Stratigraphy of the Delaware and Midland Basins

RCRL has thirty years of research experience within the Permian Basin and a clear message from this work it that it is essential to understand the shelf-to-basin connection to better understand reservoir settings. The Wolfcampian through Guadalupian sedimentology of the Delaware and Midland Basins is diverse and dynamic. The RCRL group is uniquely positioned in the southern Delaware Basin in that we have secured key outcrops that are held within private land access and we bring decades of knowledge and understanding of the Permian Basin to bear upon this very important problem of platform-to-basin correlation. This area of research will be a significant contribution to the 2017 program as highlighted by individual projects below.

Stratigraphic Architecture of Wolfcampian to Guadalupian Platforms, Shelf Margins, Slopes and Basin Fill, Delaware Basin

We will continue the investigation of the platform-to-basin architecture of the Early Permian outcrops in the Glass Mountains, including the development of an improved high-resolution stratigraphic framework that includes the influence of tectonic elements in the southern Permian Basin. In addition to the outcrop mapping effort, in 2017 we will expand the study into the subsurface of the south Delaware basin by tying the outcrop stratigraphic architecture to a few existing cored wells and numerous wireline-logs. This study aims to increase our knowledge of carbonate platform evolution and the associated potential reservoir distribution associated with

compressional tectonic and foreland basin evolution and should be of interest for companies that produce reservoirs or explore in similar settings. The outcome of this work will be beneficial to companies that work unconventional reservoirs in the southern Delaware Basin and that are interested in understanding the origin and architecture of the shelf-sourced sediments being delivered into the basin.

Guadalupian Shelf-to-Basin Framework and Analogs of the Midland Basin and Central Basin Platform

In response to increased activity in the Midland Basin (MB) and adjacent Central Basin Platform (CBP) we plan to work with operators in the North Cowden-Midland Farms-Mabee area using 3D seismic, wireline-logs, and core data to modernize the stratigraphic framework. A complex reciprocal pattern of clastic-carbonate sedimentation closely parallel to that developed from the studies that incorporated outcrop to Delaware Basin subsurface data has been partially erected by companies including OXY and Fasken, and we hope to further document this framework and apply better understood Delaware Basin terminology in the cases where we can make these comparisons. Integration of core facies/stratigraphic data with wireline-log and seismic interpretations will aid this effort. Other groups, including Pioneer and Apache, also have substantial experience in this part of the basin that and will provide steering of our stratigraphic framework as it develops. As it currently stands, important producing intervals at Midland Farms and Mabee that are currently correlated into the Grayburg Formation will be compared with their CBP equivalents to see if these make geologic sense or whether the producing intervals in the Basin might be lowstand equivalents of the Grayburg or Queen Formations. Overall, the chronostratigraphic framework of this reciprocal sedimentation pattern will be improved and a better understanding of how these systems behave as subsurface reservoirs will be developed.

Improved San Andres Flow-Unit Development using Sedimentological Elements

As a part of the continued effort to improve our models of the Guadalupian reservoir-scale stratigraphy and flow-unit architecture, a reevaluation of the classic Lawyer Canyon study area is being undertaken. We have constructed a high-resolution digital outcrop model of the key intervals and we will rebuild the geologic model one cycle at a time incorporating intracycle sedimentological elements of typical San Andres flow units which provides more insight to the lateral correlation and predictability of each flow unit.

Mechanical Stratigraphy Evolution and Fracture Development during Icehouse Conditions

Carbonate systems are unique in that highly variable rock properties can be juxtaposed during or soon after deposition. The variability and rapid evolution of rock properties is amplified in icehouse conditions when shallow-marine facies deposited at sea-level maxima can be exposed to meteoric diagenesis during the subsequent glacial maximum and associated sea-level drop.

This dramatic rock property evolution creates conditions that are favorable for early fracture development along exposures surfaces related to differential compaction and gravity loading. The RCRL group will continue to explore the rock property variability and evolution of these types of systems in outcrop exposures of both Mississippian and Virgilian mounds in the Sacramento Mountains along with investigation rock properties measured in cores from both Pennsylvanian and Wolfcampian-age mounds along the Central Basin Platform. This research is complimented by the development of finite-element, linear-elastic geomechanical models that illuminate the deformation processes responsible for the creation of early fracture networks which can be zones of high permeability or reactivated during later deformation events. Without adequate characterization of the early mechanical stratigraphy evolution, later deformation events cannot be fully understood.

Pore Network Characterization of Wolfbone, Wolfcamp, and Avalon

Previous studies of carbonate mudrock systems has revealed a diverse, yet systematic development of nano- to micropore systems that are critical to hydrocarbon production within unconventional reservoirs. By using a cadre of tools including SEM imagery, ion-milled sample preparation, and blue-fluorescent dye, the nano- and micropore network is characterized. Nano- to micropore networks within the Wolfbone, Wolfcamp, and Avalon units will be characterized in a variety of cores from the Delaware and Midland Basins.

Research Area 2 Gulf of Mexico Carbonate Reservoir Settings, Pore Systems, Fracture Character, and Margin Variability

RCRL will be developing a regional synthesis of Lower Cretaceous carbonate platform architecture around the Gulf of Mexico Basin. This multiyear project aims at documenting the variability of stratigraphic and structural architecture at the regional scale for the Lower Cretaceous shelf-margin systems with expansion of the well-developed framework in Texas to encompass the entire GOM basin. In addition, we will be exploring the high-resolution intrabasin variability of facies distribution and cycle architectures within the Albian-age ramp that prograded into the Fort Stockton embayment within the Maverick Basin of Texas as well as continuing the characterization and paleogeographic placement of a recently identified Albian marine microbiolite. Finally, the realization that numerous limited offset faults exists within the Laramide foreland is an important finding and 2017 research will examine the influence these fault zones have on Mesozoic and Paleozoic hydrocarbon production.

Regional Synthesis of Lower Cretaceous Platform Architecture around the GOM

The RCRL has worked extensively on Lower Cretaceous platform around the GOM over the past two decades. In particular, our recent work has focused on the Aptian of Central Texas and the response of carbonate systems to global oceanic events (OAEs). Our work on the earliest Cretaceous (Berriasian and Valanginian) has defined the Calvin Limestone, a new carbonate system, that is several thousand feet thick at its shelf margin. RCRL researchers have investigated a number of Albian platforms around the GOM including those in Mexico, Arizona, Texas, Florida, and Bahamas in both outcrop and subsurface. In 2017, we would plan to summarize previous results and combine new analyses of subsurface data into a regional synthesis of the stratigraphic architecture of the Aptian and Albian platform around the GOM. Within this framework we will correlate the various local stratigraphic units into an updated version of the regional stratigraphic framework proposed by Kerans and Loucks. The synthesis will also include the compilation of quantifiable parameters on the morphology and evolution of the platform architecture. The ultimate goals are to provide understanding of the various global controls (e.g., oceanic anoxic events, eustacy), regional bathymetric controls (e.g., tectonics, subsidence, antecedent topography and paleogeography), and local variability in the stratigraphic architecture. We believe this framework will improve our understanding of the distribution of petroleum systems and associated reservoirs of the Lower Cretaceous around the GOM.

Ramp Crest to Intrashelf Basin Facies Distribution and Stratigraphic Architecture of the Fort Stockton Embayment, Maverick Basin

Facies distributions, thicknesses and styles of deposition exhibit significant variability along the Cretaceous margin of the GOM. Slight variations in bathymetry can result in facies heterogeneity. Preliminary work by RCRL within the Albian-age Fort Stockton Embayment has highlighted variations in facies distributions, including an increase in the development grain-rich facies near the deepest paleobathymetric portion of the basin. Mapping the extent and style of the facies variations will be accomplished by measuring sections and mapping several outcrop exposures within Fort Stockton Embayment. This work will be synthesized in a series of stratigraphic cross sections, isopach maps, and detailed outcrop characterization interpretations.

Documentation of Lower Cretaceous (Albian) Large-Scale Microbial Mounds and Associated Rudist Mounds

Outcrop exposures in the northern Maverick Basin along the Devil's River Trend expose a series of large (up to 3 m) microbial mounds showing concentric growth structures. These are the only known Lower Cretaceous Albian microbial mounds in Texas. This unique exposure enables an excellent opportunity to document microbial mounds for depositional setting, depositional

process, and pore networks within the Albian and provides a comparison to similar facies which become reservoirs in south Atlantic basins in offshore Brazil and West Africa. This interesting section has moderate-energy microbial sediments deposited above mounds. Following a time break, large rudist caprinid mounds developed. The distribution of facies and pore types will be characterized to enable comparison to other microbial mound features and will placed into the appropriate Albian high-frequency cycle to better understand the paleogeography of this unique facies on the Lower Cretaceous platform.

Upper Cretaceous Buda and Austin Chalks Regional Study

The Buda and Austin Chalks are an integral part of the unconventional hydrocarbon system in the Texas part of the Gulf of Mexico and are also genetically and temporally linked to the prolific oil-rich Eagle Ford system. To gain a better understanding of the evolution and demise of these Gulf of Mexico drowned-carbonate platform successions, the RCRL, with cooperation of the BEG STARR Program, has undertaken a multipronged approach to the study of the Buda and Austin Chalks. Depositional patterns of these chalks will be reviewed using existing and new data (measured sections, core descriptions, wireline logs) along a proximal to distal transect so that changes in facies, oxidation, and productivity trends can be examined, along with organic richness. Significant work is ongoing in southwest Texas, and we plan to leverage that work to other areas as far to the east as the East Texas Basin.

This stratigraphic framework will be coupled with collection of basic data on cores of the Buda and Austin Chalks, including X-ray fluorescence, UCS (unconfined compressive strength), spectral gamma, minipermeameter, and velocity profiles. Petrology, petrography, and SEM analysis to explain grain and pore types are a fundamental dataset that will be used in combination with the associated data. In conjunction with the BEG-STARR program, 3D seismic analysis of fault and fracture corridors and their relationship to production trends will ultimately tie together stratigraphic and structural frameworks, along with petrophysical data and reservoir productivity, so that a more complete understanding of production trends and fairways within this Upper Cretaceous system can be achieved.

Laramide Tectonic Reactivation of Pre-existing Paleozoic Structures and the Impact on Cretaceous Fault Systems

Recent work by RCRL on Cretaceous fault systems has elucidated the connection between >30,000 faults and fracture traces and Laramide reactivation of Paleozoic structural elements in the Maverick (Mesozoic), Val Verde (Paleozoic), Midland (Paleozoic), and Delaware (Paleozoic) Basins. This connection will be further investigated in two ways. The first is the documentation of the fault type and style that can be observed primarily in roadcut exposures throughout southwest Texas, essentially a ground-truth characterization of the regional fracture pattern currently mapped in satellite photographs. The second is testing the impact that the younger fractures have on Paleozoic hydrocarbon production by examining production styles, initial production rates, GOR, and water production from fields that lie within the resolvable zone of reactivation. Examination of the produced hydrocarbon and water volumes will be analyzed with an eye toward signature characteristics of dual-permeability production styles. The results of this study could impact ongoing Permian Basin production, influence exploration uncertainty in Latin American carbonate systems and provide insight into drilling and production strategies of unconventional reservoirs of the Maverick and Permian basins.

Research Area 3 Cenozoic Carbonate Platforms and High-Resolution Stratigraphy and Diagenesis of Icehouse Isolated Platforms

RCRL research addresses a large variety of scales in order to understand the influence of tectonics on platform-to-basin stratigraphy and margin styles. With this in mind, significant effort in Tertiary systems will help to improve key controls that tectonics and sediment influx can have on carbonate reservoir and petroleum system characterization. In 2017 focus will be on three main topics: (1) the variation of platform architecture under the influence of large-scale compressional tectonics, subsidence rates and siliciclastic influx (NW Shelf of Australia and Turkey) and (2) the complexity of icehouse climate on high-frequency cycle architecture, sedimentation rates, diagenesis, and resulting reservoir heterogeneities as expressed in Pleistocene systems of the Caribbean.

Miocene Carbonate Platform in the Mut and Adana Basins, south Turkey

Recent exploration activity in the Eastern Mediterranean, southern Permian Basin and the Cuban foreland highlights the need to improve understanding of carbonate systems that develop in back-arc and foreland basins. Ongoing efforts by RCRL includes investigating Miocene carbonate platforms in South Central Turkey that developed in various tectonic settings and have contrasting platform style, size, and geometry. Two basins have been the focus of much of the work to date. The Mut Basin is a more slowly subsiding intramountain basin compared to the

Adana Basin. The overall slower subsidence rate favors the growth of a thick 10 to 45 km wide attached Miocene platform with episodes of strong basinward progradation and a nearly complete infill of the deep intramountain basin. In contrast, the high subsidence rate in the Adana Basin resulted in a narrow (1-5 km) attached back-stepping platform that developed over highly irregular topography that created a large shelf-to-basin relief. In addition, in the Adana Basin there is a significant contemporaneous clastic infill of the basin. The main emphasis of this research is to develop a detailed comparison between the stratigraphic architecture of two icehouse carbonate systems forming along different subsidence gradients. In 2017 we will construct a set of representative regional cross-sections from both basins and collect rock samples for biostratigraphy and strontium isotope analysis to improve the resolution of the existing chronostratigraphic framework. Excellent exposure of these Miocene platforms provide a range of high-quality analogs for time-equivalent plays and prospect in the Eastern Mediterranean area and in areas of variable post-tectonic subsidence.

Seismic Stratigraphy and Geomorphology of Tertiary Mixed-Carbonate Siliciclastic Depositional Systems of Northwest Shelf, Australia

There is a critical need for insight of waning tectonic systems and the role of subsidence in carbonate platform heterogeneity. This need combined with available high-resolution 3D seismic data provides a unique opportunity for a multi-year, interdisciplinary study to investigate the stratigraphic architecture and evolution of the Tertiary mixed siliciclastic-carbonate system of the Northwest Shelf of Australia. Our research tasks for 2017 are to assess large-scale controls on the distribution and architecture of the main depocenters on the shelf and in the basin for the entire Tertiary interval. Paleozoic structure, subsidence history, hinterland uplift, and export of siliciclastics are all primary controls when the system is investigated at the 100-1000's km scale. Within this larger framework, we will focus on the distribution of architectural elements and detailed stratigraphic architecture of the various depositional environments in both carbonate, siliciclastic, and mixed siliciclastic and carbonates system. In 2017, we will continue interpreting this extensive regional seismic dataset with more expansive 2D and 3D seismic surveys. We feel that stratigraphic cross-sections and geomorphologic maps at the regional scale will enable an improved understanding of the timing and extent of linked platform-to-basin systems and will highlight the degree of variability that can be found in this and analogous systems. The results of this research will benefit explorationists that investigate carbonate systems at the regional scale along continental shelves and will provide a reference case on regional factors that control the variability on carbonate platform developments.

Refinement of Icehouse Stratigraphic Patterns and Quantification of Diagenetic Overprints from Caribbean Strandplain Island Systems

Our work building a detailed stratigraphic framework for the mid-Pleistocene to Holocene carbonate strata on West Caicos Island has demonstrated first-order stratigraphic patterns particularly associated with the MIS 5e_2. Reconnaissance work on San Salvador illustrates a substantial potential to improve frameworks across the region to better calibrate both eustatic and tectonic influences on carbonate cycle development. We propose to continue this work using new data from cooperative studies on San Salvador, Providenciales, and West Caicos. This work will dovetail with parallel work on the SACROC Carboniferous platform where Mahmoud Al-Nazgahah has developed a high-resolution eustatic model that needs to be tied more closely to platform evolution in the Permian Basin. Cooperative studies with Dr. Fiona Whitaker and students at University of Bristol will expand our understanding of rates and patterns of meteoric diagenesis on West Caicos as well as hydrologic characterization of the system so that a more holistic model of deposition, early diagenesis, and structural modification can be developed. Ultimately these studies will provide insight into reservoir quality issues related to diagenesis and structural modification of shelf margins (e.g., collapse and fracture/karst-assisted diagenesis).

Fundamental Overarching Research Projects within RCRL

Within the RCRL research group we have several broad themes that we address with specific studies in order to better understand the bigger picture of carbonate systems. Each year we present updates on these efforts during the Annual Sponsors Meeting. These overarching topics include: (1) development of reservoir properties database; (2) study of tight limestones and dolomite reservoirs; (3) high-resolution imaging of nano- and micropores in carbonates; (4) carbonate rock mechanics and acoustic properties; and (5) fractures associated with carbonate fault zones. By having a longer view on these overarching research topics, we are more confident about the impact that individual studies have on broad carbonate system research and we use these reviews to identify gaps in knowledge that RCRL researchers can address. Details of each of these overarching efforts are highlighted below.

Reservoir Properties Digital Database of GOM carbonates

A new aspect of the database added this year is a carbonate reservoir-quality database based on approximately 20,000 core-plug porosity and permeability analyses from Lower Cretaceous strata of the Gulf of Mexico, Paleozoic of the Permian Basin, as well and as other areas. The data will be searchable by geographic location, formation, lithology, depth, temperature, etc. Users can plot simple scatter grams for visual inspection and the selected data can be downloaded for

further statistical analysis. This will be available in spring 2017 at http://www.beg.utexas.edu/rcrl/ members/

Origin and Petrophysics of Tight Limestone and Dolomite Reservoirs

Gas production from "tight" carbonate reservoirs is a significant unconventional resource, with important limestone examples including the Lower Cretaceous Stuart City Trend and Sligo Trend in south Texas, many of the Middle East Lower Cretaceous reservoirs, and Paleozoic dolostone examples including the Clear Fork in the Goldsmith Field, Central Basin Platform and the Lower Ordovician Ellenburger of the Fort Worth Basin. We are searching for other oil and gas fields that produce from low-permeability limestones to determine how micropores contribute to production. We have collected case histories that span stratigraphic ages and will dedicate most 2017 efforts to document case histories from the Paleozoic, especially dolostone reservoirs. An important part of this study is investigating and cataloging of micropore carbonate reservoirs worldwide. In this project, we have defined the types, origins, temporal and spatial distributions, and petrophysical properties of microporous carbonates. We have recently extended our research into dolomites. We have made strong progress in defining the origin of different micropores, and now we need to document enough case histories in order to summarize their petrophysical characteristics and how to predict the regional distribution of micropores in limestones and dolomites.

Micro-CT-Scan and Other Ultrahigh-Resolution Analysis of Micropores in Carbonates

The flow in microporous carbonates containing nanopores and micropores may not be the same as in megapore carbonates. We have initiated a new research effort where we are micro-CT scanning millimeter-sized plugs of microporous carbonates. The 3D scans will be analyzed using FEI's Avizo Beta 9.0 software that allows us to calculate permeability in multiple directions, simulate flow, outline in 3D the pore networks, and define continuity of pore flow paths. We are also looking at methods of quantifying the effects of micropores in dual pore networks. This includes developing methods of quantifying micropores and their distribution from the thin-section level to the field scale. This will include integrating petrophysical analysis with thin-section point counts to understand the contribution of each pore type. The more regional quantification effort will be based on relating the pores to elements within the facies and how these pore controlling elements vary field wide.

Carbonate Rock Mechanics and Acoustic Properties Research

This long term project investigates the change in petrophysical and mechanical properties associated with diagenetically-modified pore types within known primary textures and/or lithofacies. This characterization effort will be followed by an assessment of the best rock physics

model to reproduce the experimental measurements. The ultimate goal is to calibrate and evaluate the ability of various rock physics models to predict the wireline log response and seismic response associated with changes in pore types in carbonate rocks. In 2017, we will select carbonate cores that exhibit a simple pore type change within a single lithofacies, preferably within the same interval. This project relies on collecting a wide range of nondestructive data on the core and calibrate those measurements with strategically selected MicroCT scan, petrophysical, acoustic and mechanical measurement as well as detailed petrography on 1”-core plugs. Based on those data, we will characterize and quantify geometrical parameter of the pore network in 2D (thin section) and 3D (CT scan) through image analysis, calculate mechanic moduli from acoustic properties and stress-strain curves, and integrate and compare laboratory measurements with wireline logs. Finally, we will then be able to critically evaluate which rock-physics model performs the best based on core measurement (for instance compare DEM extended Xu-White model and Extended Biot Theory model) and perform rock-physics based transforms of wireline-log suites to predict acoustic signature at the wireline-log and seismic scale.

Fractures Associated with Carbonate Fault Zones

The catalog of well-documented fault-related fracture systems within carbonate systems is limited yet a recent surge of activity in Latin and South America along with ongoing activity within the onshore US highlights the need for these analog systems to be documented. In 2017, three different outcrops will be characterized to a very high level of detail. Two are within Albian-age reservoir analogs and the third is within mixed carbonate-siliciclastic mudstones of Cambrian and Ordovician age. For all three exposures a detailed 3D photogrammetry model has been developed and will be characterized in detail for fracture style, intensity, and distribution. Furthermore, 3D stochastic models will be constructed for interrogation and scenario testing of fracture permeability upscaling and potential flow-simulation studies. Raw data, fracture maps, 3D stochastic models (FracMan), and 3D point clouds of the photogrammetry model will be made available in digital form to RCRL members for individual company interrogation or inclusion in proprietary company catalogs.

SUMMARY

RCRL is an integrated carbonate research group whose major mission is to use outcrop and subsurface geological, geophysical, and petrophysical data as the basis for developing new and integrated methodologies for a better understanding and description of the 3D carbonate reservoir system. Our unique expertise addresses research questions in carbonate shelf to basin systems and at scale of investigation from nanopores to basin architecture. Our 2017 research program is organized around three high-level research directions: (1) Early Permian shelf-to-basin synorogenic to early post-orogenic stratigraphy of the Delaware and Midland Basins; (2) Gulf of Mexico carbonate reservoir settings, pore systems, fracture character, and margin variability; and (3) Cenozoic carbonate platforms and high-resolution stratigraphy and diagenesis of icehouse isolated platforms. Research questions for each theme are developed using both subsurface and outcrop analogs. We emphasize quantifying what we observe so that our research is applicable to reservoir models and valuable in providing predictive relationships and conceptual tools for reservoir characterization. Our research focus areas, themes, and topics have been developed out of our experience and feedback from our sponsorship.

In 2017, the annual RCRL Industrial Associates contribution to the program is $55,000 per year. We encourage sponsors to commit to a 2-year agreement so that we can better plan a longer-range research program and reduce the time and effort in securing agreements. A 2-year agreement is currently being offered at $50,000 per year for the next 2 years (total of $100,000, with $50,000 due at the beginning of each year).

If you have any questions on any aspect of the RCRL Carbonate Reservoirs Research Program, please contact Charlie Kerans (512-471-4282 or ckerans@jsg.utexas.edu) or Bob Loucks (512-471-0366 or bob.loucks@beg.utexas.edu).

APPENDIX A: RECENT AND ACTIVE RCRL STUDENTS

Students in Progress

Ahmed Alnahwi, Ph.D. Candidate (joint student between RCRL and MSRL, expected completion, 2017) – Research objective: Characterize lithofacies and pore networks in the Upper Cretaceous Eagle Ford Shale in south Texas and relate to wireline-log analysis. Co-supervisors, R. Loucks and W. Fisher

Andrea Nolting, Ph.D. Candidate (expected completion, 2017) – Research objective: Improved understanding of the controls on shelf margin faulting and failure, including rock property evolution, current and pre-existing geometry, and eustacy. Co-supervisors, C. Zahm and C. Kerans.

Ben Smith, Ph.D. Candidate, (expected completion, 2019) – Research objective: High-resolution cycle and sequence architecture of the Seven Rivers Formation, north wall of McKittrick Canyon. Co-supervisors Charlie Kerans and Scott Tinker.

Chris Hendricks, M.Sc. Candidate (Joint student between RCRL and STARR; expected completion, December 2016) – Research objectives: Chemolithostratigraphy of the Upper Cretaceous Buda Formation and Austin Chalk Group, central and south Texas: Lithofacies constraints from geochemical data integration. Co-supervisors, Robert Loucks and Harry Rowe.

Mahmoud Al-Nazaghah, Ph.D. Candidate (expected completion, 2018) – Research objectives: Origin and architecture of glacioeustatically forced reservoir flow units, SACROC field and equivalent outcrop datasets. Co-supervisors, Charlie Kerans, and Chris Zahm.

Mohammed Fallatah, Ph.D. Candidate (expected completion, 2018) – Research objectives: High-resolution stratigraphic analysis of the Hanifa Formation in outcrop and subsurface reservoirs, Saudi Arabia. Supervisor, Charles Kerans

Nathan Tinker, M.Sc., (expected completion, Dec. 2016) – Research objective: Integrated structural-stratigraphic analysis of compaction-related fracturing in carbonate buildups and associated cover strata. Co-supervisors, Xavier Janson and Chris Zahm.

Peter Schempher, M.Sc., (expected completion, 2018) – Research objective: Fusselmen of the eastern Midland Basin. Co-supervisor, Bob Loucks and Qilong Fu.

Peter Soto-Kerans, M.Sc. Candidate (Joint student between RCRL and STARR; expected completion, 2017) – Research objectives: Stratigraphic architecture, depositional setting, and lithofacies of the Upper Glen Rose in the southeastern East Texas Basin and their application to conventional and unconventional reservoirs. Supervisor, Robert Loucks.

Reynaldy Fifariz, Ph.D. Candidate (expected completion, 2017) – Research objectives: Integrating core, well log, seismic, and outcrop analogs to propose a regional architecture of faulted carbonate platforms of the East Java area, Indonesia. Co-supervisors, X. Janson and C. Kerans; Committee: Ron Steel, Craig Fulthorp, and Ben Sapiie.

Taylor Canada, M.Sc. Candidate (expected graduation, 2018) – Research objectives: High-resolution stratigraphy of the Wolfcampian Powwow and Hueco Formations exposed in the Wylie Mountains, Southern Delaware Basin. Supervisor, Charles Kerans.

Yasar Alzayer, Ph.D. Candidate (expected completion, 2018) - Research objective: Characterization and geomechanical modeling of mud mounds and flank margin strata during icehouse climate, Sacramento Mountains, New Mexico, Co-supervisors, Chris Zahm and Charles Kerans.

Recently Graduated

Kris Voorhees, M.Sc., (2016) Anatomy, dimensions and significance of the penultimate Yates tepee-shelf crest complex, G25 Hairpin HFS, Guadalupe Mountains, New Mexico and Texas. Supervisor, Charlie Kerans.

Ozen Gurbuz, M.Sc., (2016) Mechanical stratigraphy of folded Lower to Upper Cretaceous carbonates of the Mardin Group, Eastern Turkey. Supervisor, X. Janson

Gregory Hurd, Ph.D., (2016) Interpreting and modeling processes of deposition and deformation on carbonate slopes. Co-supervisors, C. Kerans and X. Janson

Kyle McKenzie, M.Sc., (2016) Outcrop-derived facies model and cycle architecture of the Tansill G27-G-28 high-frequency sequences, Rattlesnake Canyon, New Mexico. Supervisors, C. Kerans and Robert Loucks

Nick Danger, M.Sc., (2016) Facies mapping and origin of foreshore-upper shoreface ooid grainstones in strandplain systems, West Caicos. Supervisor, Charlie Kerans.

Jeff Sitgreaves, M.Sc., (2015) Shelf-to-basin architecture and facies variability of a Cretaceous intrashelf basin in the northwest Gulf of Mexico. Supervisor, Charlie Kerans

Chris Liu, M.Sc., (2015) Lithofacies and associated dual mega/micropore network within the Albian Sunniland carbonates in south Florida. Emphasis with be on origin and characterization of the lithofacies and associated pore networks. Co-supervisors, Charles Kerans and Robert Loucks.

Maren Mathisen, M.Sc. (2014) Temporal and spatial evolution of the Cave Graben Fault System, Guadalupe Mountains, New Mexico; Co-supervisors, C. Zahm and C. Kerans

Rebekah Simon, M.Sc. (2014) Syndepositional fault control on dolomitization of a steep-walled carbonate platform margin, Yates Formation, Rattlesnake Canyon, New Mexico. Co-supervisors, C. Kerans and C. Zahm

Gordon Smith, M.Sc. (2013) Fault and fracture systems related to reactivation of pre-existing structural elements, Devil's River Uplift and Maverick Basin, Texas. Co-supervisors, C. Zahm and W. Fisher

Alex Parker, M.Sc. (2013) Outcrop Characterization of Ooid Grainstones in the Grayburg Formation, Guadalupe Mountains, New Mexico. Supervisor, C. Kerans

Sam Hiebert, M.Sc. (2013) High-Resolution Sequence and Chemostratigraphic Correlations of the Grayburg Formation—Shattuck Escarpment and Plowman Ridge—Testing Models of Shelf-to-Basin Frameworks. Supervisorm C. Kerans

Stephanie Wood, M.Sc. (2013) Lithofacies, Depositional Environments, and Sequence Stratigraphy of the Pennsylvanian (Morrowan-Atokan) Marble Falls Formation, Central Texas. Co-supervisors, R. Loucks and S. Ruppel

APPENDIX B: RECENT RCRL PUBLICATIONS

2016

Ambrose, W. A., Dutton, S. P., and Loucks, R. G., 2016, Depositional systems, facies variability, and reservoir quality in shallow-marine reservoirs in the Eocene Upper Wilcox Group in Fandango Field, Zapata County, Texas: GCAGS Journal, v. 5, p. 73-94.

Brooks, D., X. Janson, and C. Zahm, 2016, The effect of sample volume on micro-rebound hammer UCS measurements in Gulf Coast Cretaceous carbonate cores: Gulf Coast Association of Geological Societies Journal, v. 5, p. 189–202.

Dutton, S. P., Ambrose, W. A., and Loucks, R. G., 2016, Diagenetic controls on reservoir quality in deep upper Wilcox sandstones of the Rio Grande delta system, South Texas: GCAGS Journal, v. 5, p. 95-110.

Frébourg, G., Ruppel, S. C., Loucks, R. G., and Lambert, J., 2016, Depositional controls on sediment body architecture in the Eagle Ford/Boquillas system: Insights from outcrops in west Texas, United States: AAPG Bulletin, v. 100, no. 4, p. 657-682, http://doi.org/10.1306/12091515101.

He, Y., C. Kerans, H. Zeng, X. Janson, and S. Z. Scott. 2016, Reservoir-scale chronostratigraphic significance of seismic reflections of a strongly prograding shelf margin: 3D outcrop-constrained seismic models, SEG Technical Program Expanded Abstracts 2016: Society of Exploration Geophysicists. 1818-1823.

Hurd, G. S., C. Kerans, S. Fullmer, and X. Janson. 2016, Large-Scale Inflections in Slope Angle Below the Shelf Break: A First Order Control On the Stratigraphic Architecture of Carbonate Slopes: Cutoff Formation, Guadalupe Mountains National Park, West Texas, USA. Journal of Sedimentary Research, 86, no. 4,336-362.

Loucks, R. G., Kerans, Charles, Zeng, Hongliu, and Sullivan, P. A., 2017 (in press), Documentation and characterization of the Lower Cretaceous (Valanginian) Calvin and Winn carbonate shelves and shelf margins, onshore northcentral Gulf of Mexico: AAPG Bulletin, (February 2017), 24 p.

Loucks, R. G., et al., in press, Pore types, pore-network analysis, and pore quantification of the lacustrine shale-hydrocarbon system in the Late Triassic Yanchang Formation in the southeastern Ordos Basin, China: Interpretation, (February 2017).

Loucks, R. G., and Fu, Qilong, 2016, Origin and characterization of the lithofacies and Dual micropore/macropore network in Pennsylvanian (Early Desmoinesian) Caddo shelf-buildup complexes, Stephens County, North Central Texas: GCAGS Journal, v. 5, p. 1-24.

Loucks, R.G., and Reed, R. M., 2016, Natural microfractures in unconventional shale-oil and shale-gas systems: Real, hypothetical, or wrongly defined? GCAGS Journal, v. 5, p. 64-72.

Nolting, A., Zahm, C.K., Kerans, C., and D. Brooks, 2016, Spatial and temporal characterization of mechanical rock properties from West Caicos, British West Indies, American Rock Mechanics Association 16-705, p. 1-14.

Peng, S., and Loucks, R. G., 2016, Permeability measurements in mudrocks using gas-expansion methods on plug and crushed-rock samples: Marine and Petroleum Geology, v. 73, p. 299-310, http://doi.org/10.1016/j.marpetgeo.2016.02.025.

Peng, S., Hassan, A., and Loucks, R. G., 2016, Permeability estimation based on thin-section image analysis and 2D flow modeling in grain-dominated carbonates: Marine and Petroleum Geology, v. 77, p. 763-775, http://doi.org/10.1016/j.marpetgeo.2016.07.024.

Qiao, Z., X. Janson, A. Shen, J. Zheng, H. Zeng, and X. Wang. 2016, Lithofacies, architecture, and reservoir heterogeneity of tidal-dominated platform marginal oolitic shoal: An analogue of oolitic reservoirs of Lower Triassic Feixianguan Formation, Sichuan Basin, SW China. Marine and Petroleum Geology, 76,290-309.

Smith, G., C. Zahm, and C. Kerans, 2016, Mechanically-partitioned deformation related to reactivated oblique slip faults, Pecos River Canyon: Gulf Coast Association of Geological Societies Journal, v. 5, p. 238–252.

Zahm, C., J. Lambert, and C. Kerans, 2016, Use of unmanned aerial vehicles (UAVs) to create digital outcrop models: An example from the Cretaceous Cow Creek Formation, Central Texas: Gulf Coast Association of Geological Societies Journal, v. 5, p. 180–188.

2015

Decker, L., Janson, X., and Fomel, S., 2015, Carbonate reservoir characterization using seismic diffraction imaging: Interpretation, v. 3, no. 1, p. SF21-SF30.

Janson, X., Lee, K., Zahm, C., and Kerans, C., 2015, Ground-penetrating radar imaging of Albian rudist buildups, central Texas: Interpretation, v. 3, no. 3, p. SY67-SY81, http://doi.org/10.1190/INT-2014-0273.1.

Loucks, R. G., Reed, R. M., and Ambrose, W. A., 2015, Analysis of pore networks and reservoir quality of the Upper Cretaceous Woodbine sandstone in the high-recovery-efficiency, giant East Texas Field: GCAGS Journal, v. 4, p. 88-108.

Peng, S., Yang, J., Xiao, X., Loucks, R. G., Ruppel, S. C., and Zhang, T., 2015, An integrated method for upscaling pore-network characterization and permeability estimation: example from the Mississippian Barnett Shale: Transport in Porous Media, v. 109, no. 2, p. 359-376, http://doi.org/10.1007/s11242-015-0523-8.

Phelps, R. M., Kerans, C., Da-Gama, R.O.B.P., Jeremiah, J., Hull, D., and Loucks, R. G., 2015, Response and recovery of the Comanche carbonate platform surrounding multiple Cretaceous oceanic anoxic events, northern Gulf of Mexico: Cretaceous Research, v. 54, p. 117-144, http://doi.org/10.1016/j.cretres.2014.09.002.

Reed, R. M., and Loucks, R. G., 2015, Low-thermal-maturity (<0.7% VR) mudrock pore systems: Mississippian Barnett Shale, southern Fort Worth Basin: GCAGS Journal, v. 4, p.15-28.

2014

Janson, X., Lucia, F. J., Jennings, J. W., Bellian, J. A., AbuBshait, A. A., Al-Dukhayyil, R. K., Mueller, H. W., and Cantrell, D., 2014, Outcrop-based 3D geological and reservoir model of the uppermost Khuff Formation in central Saudi Arabia, in Pöppelreiter, M., ed., Permo-Triassic Sequence of the Arabian Plate: EAGE Special Publication, p. 269-302.

Phelps, R. M., C. Kerans, J. Jeremiah, R. O. Da-Gama, D. Hull, and R. G. Loucks, in review, Response and recovery of the Comanche carbonate platform surrounding multiple Cretaceous Oceanic Anoxic Events, northern Gulf of Mexico, 157 pgs.

Loucks, R. G., and Reed, R. M., 2014, Scanning-electron-microscope petrographic evidence for distinguishing organic-matter pores associated with deposition organic matter versus migrated organic matter in mudrocks: GCAGS Journal, v. 3, p. 51-60.

Loucks, R. G., and H. D. Rowe, 2014, Upper Cretaceous Niobrara Chalk in Buck Peak field, Sand Wash Basin, NW Colorado: Depositional setting, lithofacies, and nanopore network; SPE/AAPG/SEG Unconventional Resources Technology Conference, 25-27 August , Denver, Colorado, USA, 13 p. (DOI: http://dx.doi.org/10.15530/urtec-2014-1918913).

2013

Clayton, J., and C. Kerans, 2013, Reservoir compartmentalization of a deep-water ooid fan, Happy Field, Permian Basin, in Verwer, Klass, and Playton, Ted, Editors, Deposits, Architecture and Controls of Carbonate Margin, Slope and Basinal Settings, SEPM Special Publication 105, p. 359-383.

Kerans, C., Playton, T., Phelps, R.A., and Scott, S. Z., 2013, Ramp-to-Rimmed Shelf Transition in the Guadalupian (Permian) of the Guadalupe Mountains, West Texas and New Mexico, in Verwer, K., and Playton, T., Editors, Carbonate Slopes, SEPM special publication no. 105, p. 26-49.

Loucks, R. G., Lucia, F. J., and Waite, L. E., 2013, Origin and description of the micropore network within the Lower Cretaceous Stuart City Trend tight-gas limestone reservoir in Pawnee Field in South Texas: GCAGS Journal, v. 2, p. 29-41.

Lucia, F. J. and Loucks, R. G., 2013, Microporosity in carbonate mud: Early development and petrophysics: GCAGS Journal, v. 2, p. 1-10.

Michelena, R.J., Godbey, K., Wang, H., Gilman, J, Zahm, C.K., 2013, Estimation of dispersion in orientations of natural fractures from seismic data: application to DFN modeling and flow simulation, SEG-URTEC Special Issue, The Leading Edge, p. 1502-1512.

Phelps, R. M., Kerans, C., Loucks, R. G., Gama, R., Jeremiah, J., and Hull, D., 2013, Oceanographic and eustatic control of carbonate platform evolution and sequence stratigraphy on the Cretaceous (Valanginian–Campanian) passive margin, northern Gulf of Mexico: Sedimentology, p. 1-36.