Executive Summary and Prospectus for 2015
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Research Plans for 2015

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

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Reservoir Characterization Research Laboratory

Research Plans for 2015

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 recovery factors.

FUNDING

We invite you to participate in the continuation of the RCRL Carbonate Reservoirs Research Program for 2015. A list of recent sponsors is presented in Table 1. In 2015, 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 can offer a 2-year (2015 and 2016) 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 run continuously since 1987, maintaining strong company sponsorship each year (Table 1). In 2014, RCRL was supported by 33 companies.
Table 1. 2014 RCRL Sponsors

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Sponsors are currently interested in a range of domestic and international carbonate reservoirs, ranging in age from Ordovician to Tertiary. This enrollment, supplemented by other grants, supports between six and nine professional staff members and varying numbers of graduate student research assistants, as well as excellent computer, editing, and graphics services.

Principal Staff

Dr. Charles Kerans, Geology Professor, Principal Investigator
Dr. Robert Loucks, Senior Research Scientist, Principal Investigator
Mr. F. Jerry Lucia, Senior Research Scientist, Geological Engineer
Dr. Xavier Janson, Research Scientist, Geologist
Dr. Christopher Zahm, Research Associate, Geologist
Dr. Harry Rowe, Research Scientist, Isotope Geochemist
Mr. Josh Lambert, Research Technician
Ms. Stephaine Lane, Project Coordinator

Associate Staff

Dr. Gregory Frébourg, Research Associate, Geologist
Dr. Sheng Peng, Research Associate, Geologist
Dr. Steve Ruppel, Senior Research Scientist, Geologist
Dr. Hongliu Zeng, Senior Research Scientist, Geophysicist
Staff members have had extensive industry experience or have worked closely with industry, and they are well aware of the challenges and questions facing development geoscientists and engineers. We are also proud of our graduate students (Appendix A) associated with RCRL, who have included several award-winning students, many of who are now working in industry.

**AREAS OF INTEREST**

Three primary research focus areas compose the RCRL research program: (1) characterization of carbonate-outcrop analogs, (2) characterization of carbonate subsurface reservoirs, and (3) seismic and geomodeling of both subsurface and outcrop analogs. Our research-focus areas, themes, and topics have been developed out of our experience and feedback from our sponsorship.

We are an integrated program that incorporates established and new research methodologies. Our research is on select datasets, both outcrop and subsurface, that address specific application to subsurface challenges. Our basic approach is to work from rocks to flow modeling, within the context of continuing to develop basic principles and techniques that can be applied to exploration and production of hydrocarbons. We emphasize quantifying what we observe so that our research is (1) applicable to modeling reservoirs and (2) valuable in providing predictive relationships and conceptual tools for reservoir characterization.

**INFORMATION TRANSFER**

**General**

Our industrial sponsors receive research results at annual review meetings, in short courses, during mentoring activities, in publications and DVD’s, and on our continually updated, members-only RCRL website database (http://www.beg.utexas.edu/rcrl/members/). This online searchable database 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 company has a unique identification logon and password, which are renewed each year of sponsorship. This database includes previous, annotated presentations, maps, core photos, porosity and permeability data, digital-outcrop reservoir models, core descriptions, and field guides from past and current RCRL field trips.
Workshops and Field Seminar

In addition to an annual review meeting and associated field trips, we also conduct carbonate reservoir characterization short courses and field workshops for sponsor companies during the year. In the spring of 2014, we conducted a paleokarst seminar that consisted of classroom, core workshop, and fieldwork activities where we reviewed carbonate and evaporite paleokarst reservoir development. This year we will run two field seminars.

Modern and Pleistocene Depositional and Structural Patterns, Caicos Platform, Providenciales, BWI

The Holocene-Pleistocene exposures of the Caicos platform are a must-see for carbonate sedimentologists working on a range of play types and facies associations. The compact nature of the Caicos Platform allows assimilation of all essential carbonate facies tracts in an efficient 5-day excursion. The RCRL group has been working with Steve Bachtel of Chevron and Bill Morgan (formerly of Conoco-Phillips) over the past 5 years to refine a trip targeted at carbonate graduate students. This spring we will run a focused 5-day class for RCRL sponsors that includes day-long projects in the tidal flats, on the classic Ambergris ooid complex (including oolitic tidal flats, foreshore-shoreface, and wind-driven wave bar), reef systems (barrier reef-reef flat-back reef sands, fringing reef, and patch reefs), Pleistocene and modern foreshore-shoreface and spur-and-groove fringing reefs of West Caicos, and fracture-controlled permeability and failure features.

Workshops will be held using lecture and core material to drive home field stops, and core samples, drone imagery, RTK-GPS and lidar will be used to illustrate new approaches to data collection and analysis.

The fieldtrip will be 5 full days plus travel days to and from Providenciales. The trip will begin and end in Providenciales, BWI, and will be limited to 15 participants, though it can run again in November if sufficient interest exists. This trip will involve several stops where swimming and snorkeling are important and the trip should be considered moderately physically demanding. Dates for the course are not finalized, but will be in early May.

Upper Cretaceous Drowned Platform Conventional and Fractured Reservoir Outcrop Analogs; Del Rio Area, Southwest Texas

The second field seminar will be to an area just west of Del Rio, Texas where excellent roadcuts of the Upper Cretaceous carbonates are exposed. The Buda and Austin Chalk sections are well-known fracture plays and the Eagle Ford is a leading unconventional shale oil and gas play. The trip will stress the understanding of deeper water carbonate deposition on a drowned shelf. We will bring along some cores representative of equivalent reservoirs in the subsurface. The field
seminar is three days long and physically easy. The dates will be in either April or May and will be announced in January 2015 along with details on how to register.

**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.

Xavier Janson did another 10 days of fieldwork in the Permo-Triassic carbonates of the Sichuan Basin in China examining Upper Permian reef and Lower Triassic oolitic shoal complexes as part of a 3-year research collaboration with PetroChina.

In January 2014, Chris Zahm, Josh Lambert, and Ben Cutright traveled to Denver to collect UCS and UPV data on key cores within Whiting Petroleum’s Red Tail area in northern Colorado. A follow up trip was conducted in August to Whiting to present preliminary results of the logging and to add two additional cores to the database. Much of this work was presented at the October 2014 Annual Sponsors meeting.

Charlie Kerans, Xavier Janson, and Chris Zahm are currently discussing projects with Statoil on a variety of future projects, as well as with KinderMorgan and OXY USA on future projects at Yates field and along the Northwest Shelf of the Permian Basin.

Jerry Lucia and Bob Loucks worked with US EnergyCorp, on reservoir quality of the Upper Cetaceous Buda Formation in south Texas, by reviewing cores and thin sections. They produced several reports on the lithofacies, pore networks, and wireline-log analysis. The summary of this work was presented at the October 2014 Annual Sponsors meeting.

Bob Loucks interacted with several companies, including (1) Pioneer, relative to the pore network in the Lower Cretaceous Stuart City Trend; (2) PetroChina, where he presented several talks on carbonate and evaporite paleokarst; (3) PetroChina, where he completed description of several cores from the Sichuan Basin, Upper Permian reef and lower Triassic section; (4) ConocoPhillips in their Houston office and Statoil in their Austin office where he conducted a 3-hour seminar; and (5) Oxy on the reservoir architecture and pore networks of the Clear Fork section in Goldsmith field (Ector Co., Texas).

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 learns together through hands-on data analysis of real production data and issues, 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 who are now working in industry. Charlie Kerans, a professor in 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. Xavier Janson, Jerry Lucia, Chris Zahm, Steve Ruppel, Harry Rowe, Gregory Frebourg, 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 carbonates 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 2015

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. The RCRL brand has been developed by combining three focus areas: (1) carbonate outcrop reservoir analogs, (2) integrated subsurface carbonate reservoir characterization, and (3) geomodeling and geologically realistic modeling of seismic, matrix pores, karst, and fractures. In the 28 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/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.

Within the primary focus of RCRL, six thematic areas encompass the expertise of the consortium: (1) remote-sensing characterization (e.g., photogrammetry, both ground and through the use of unmanned aerial vehicles (UAVs), lidar, and ground-penetrating radar), (2) geologic framework development (e.g., stratigraphic and structural architecture and mechanical stratigraphy), (3) nonmatrix pore characterization (e.g., fractures and karst cavities
and vugs), (4) tight carbonate reservoirs (pore types in these varied reservoirs), (5) reservoir characterization (e.g., identification and distribution of relevant properties important to enhanced hydrocarbon recovery), and (6) analog-based synthetic seismic and geomodeling of facies, fractures, and karst.

For 2015, we are focusing research on seven main themes: (1) reservoir architecture and structural style of carbonate shelf-to-basin transitions, (2) mechanical stratigraphy and the influence on fractured reservoirs, (3) evaporite paleokarst systems, (4) Tertiary carbonate systems, (5) tight carbonate reservoirs (including micropore-dominated reservoirs), (6) mechanical and acoustic characterization of carbonate rocks, and (7) finite element modeling of fractures and deformation in carbonate systems. We are also integrating isotopes and geochemistry (much of it based on XRF data) into our research projects as Dr. Harry Rowe develops new research approaches using these techniques in chemostratigraphy and paleodepositional interpretations. Dr. Rowe has developed a state-of-the-art isotope and XRF laboratory here at the BEG.

RCRL research projects were selected using the following criteria: (1) topics that specifically address hydrocarbon recovery issues important to our sponsors, (2) multiple levels of integration within our themes, (3) maximization of the abilities and experience of our research group, and (4) the potential to make the greatest impact on fundamental understanding of the carbonate reservoir system.

RESERVOIR ARCHITECTURE AND STRUCTURAL STYLE OF CARBONATE SHELF-TO-BASIN TRANSITIONS

The dynamics of platform-to-slope transitions (including characteristics and width of key facies tracts, density of syndepositional and later reactivated fractures, scale of margin collapse, development of growth faulting and fracturing vs. extensive collapse, timing and drivers for collapse and debris-flow megabreccia generation, and associated changes in permeability pathways) are critical to an understanding of production in fractured steep-rimming microbial systems. Field applications of this analog work include Tengiz, Kashagan, Korolev, and Karachaganak. Similar large-scale collapse is observed in the Cretaceous of the Gulf of Mexico margin, such as along the margins of the Golden Lane platform and Stuart City margin. Four areas of research link to this theme in 2015. Work continues in refining the Guadalupian model through numerical modeling as well as field work in the Seven Rivers shelf to shelf-edge transition and through documenting one of the larger exposure events during Capitan deposition. The Glass Mountain section permits study of shelf-to-basin transitions across a wide range of structural settings and Wolfcamp through Leonardian age. The Cretaceous platform to basin transition will be examined at regional scale focusing on the Aptian Cow Creek-Pine Island and Hensel-Bexar profiles as well as a Texas-wide comparison of Maverick and East Texas basins.
Finally, West Caicos will provide a setting for research on both architecture of shelf-edge grainstones and for characterizing the steep-rimmed margin of the Caicos platform.

**Integrated Stratigraphic/Structural Framework of the Guadalupe Mountains**

The Guadalupe Mountains remain a key laboratory for our research and training in the stratigraphy and structural attributes of steep-rimmed platforms. Study of the interaction of a prograding, steep-rimmed platform (Capitan system) and its genetically linked syndepositional faults and fractures remains a high priority for 2015. During 2014 we completed a phase of fault-fracture mapping in Rattlesnake and Slaughter Canyons using a combination of structure, stratigraphy, and diagenetic overprints. Quantitative finite-element models (i.e., Elfen) will be constructed to improve understanding of the early-formed fractures in shelf margin systems. Through these modeling efforts we plan to (1) refine material properties characterization of Permian strata; (2) better understand the evolution of shelf margin deformation; (3) become predictive for where deformation occurs; and (4) make significant progress toward a coupled model for Permian deformation and diagenesis.

Through work of Kerans and students, we now have a dataset of more than 100 grainstone geobodies from San Andres, Grayburg, Queen, Yates, and to a lesser extent, Tansill Formations that provides a good understanding of the continuity and sedimentologic affinity of these grainstone bodies within a stratigraphic framework, providing a basis for subsurface geomodeling. The Seven Rivers Formation stands out as the one major stratigraphic interval that has not been mapped on a cycle-scale to determine how grainstone deposits develop as the early stages of Capitan reef growth and associated tepee island complexes evolve. Ben Smith (M.Sc.) will undertake a detailed high-resolution stratigraphic analysis of the Seven Rivers along the updip portion of the north McKittrick wall in the area previously worked by Scott Tinker and Neil Hurley to attempt to document the shelf crest (tepee complex) to reef-flat architecture in the area, as well as capturing any evidence for syndepositional deformation in this part of the Guadalupe Mt. section.

An important question in the Capitan-equivalent Guadalupian section is the magnitude of eustatic fluctuation across sequences and the role that this variability played in shaping the high-frequency sequences and associated sequence boundaries. A long-held, but difficult to demonstrate belief is that there was only minor amplitude eustatic fluctuations during Capitan deposition and that the reef stayed at a near-constant sea-level through time. The work of Kosa and Hunt (1996) and Hunt et al (2002) stressed the importance of subaerial exposure in development of syndepositional fault/fracture systems observed in Slaughter, Rattlesnake, and Walnut Canyons and pointed to the Hairpin/Triplet interval as bracketing this exposure event. Over the past 5 years working the Yates interval in the McKittrick through Walnut Canyon area it has become clear that the Hairpin or G25 sequence is unique in recording an extraordinary eustatic fall during the late Guadalupian. This sequence displays a dramatically expanded shelf-
crest tepee-pisolite complex and has by far the most extensive tepee-pisolite development in the Guadalupes. It also shows evidence of subaerial exposure expanding out across the outer shelf and approaching the reef itself. Further, this exposure surface is immediately followed by widespread deposition of lower Triplet sandstones across the shelf and into the uppermost Bell Canyon (Ramsey) sandstones of the basin. This unique aspect of the Hairpin sequence has not yet been targeted specifically and this leaves unanswered the question of how the reef and shelf are affected during a major drop in relative sea-level. Kris Voorhees (M.Sc.) will work this specific HFS from landward of the shelf crest to the reef flat in several canyons where it is well exposed including McKittrick, Slaughter, Rattlesnake, and Walnut canyons. We hope to document the changing styles of deposition during Hairpin time and be better informed about the controlling processes for this unique and important unit.

Platform-to-Basin Architecture of Lower Permian Carbonates in the Glass Mountains

Glass Mountain outcrops are located in the south part of the Delaware Basin, just in front of the terminal thrust of the Marathon orogenic belt near the Hovey Channel. They are therefore critical to an understanding of the regional paleogeography and the stratigraphic evolution of the south part of the Permian Basin in general. Our long-term goals are to establish a robust sequence tectono-stratigraphic framework in the southern Delaware Basin and compare it with the well-established framework of the Hueco, Sierra Diablo, and Guadalupe Mountains. Because of the paleogeographic and tectonic setting, these outcrops also provide a unique opportunity to gain an understanding of the development of carbonate platforms, as well as slope and basins in an active compressional tectonic setting.

Our main research goals are to

1. Understand and unravel the combined tectonic and eustatic influence on the stratigraphic architecture of the Lower Permian mixed carbonate-siliciclastic system.
2. Evaluate the influence of a northward-migrating thrust front on the carbonate-platform architecture.
3. Characterize the controls of platform development, margin geometry and trajectory, and the characteristics of the slope system for delivery of deepwater sediments to the basin.
4. Expand our models of carbonate slopes by including examples of carbonate-slope architecture in an active tectonic setting.
5. Explain the regional paleogeography and its control of Capitanian reef development.

Seismic and Stratigraphic Architecture of Leonardian Prograding Margin and Slope

In 2015, we will investigate the evolution along strike of a Lower Clear Fork prograding margin on the east side of the Central Basin Platform using a dataset donated by OXY Permian. The project will use several 3D seismic datasets to map in details the smallest seismically resolvable packages along strike and to investigate the role of antecedent topography (e.g., older margin) as
well as deeper structural control on the style and amount of platform progradation, and the internal architecture and potential reservoir developments in the Lower Clear Fork. We will also integrate existing core and wireline-log information to characterize the platform top-to-margin reservoirs architectures and existing remaining potential in this already well developed interval.

**Morphometric Analysis of Carbonate Slope Deposits**

We are planning on extending our morphometric study of carbonate slope systems using publically available bathymetric data, literature, and our own datasets. In 2014, we focused on carbonate channels. In 2015, we will refine and complete the channel study, and compile the results in a database. We will also start expending into the nonconfined flows such as MTCs (mass transport complex) and fans. We are currently investigating options to acquire our own dataset on the Southern Florida shelf where we discovered last year, well-preserved (if not currently active) modern sinuous carbonate channel- levee complexes.

**Cretaceous Carbonate Platform – Regional Framework and Link to Aptian Ramp and Albian Intrashelf Basin**

The Aptian shelf-to-basin profile was the focus of the 2014 fall field excursion and additional work will be done to develop a better link between shoreline and deep-shelf organic-rich facies. Some outstanding outcrops along the Lake Travis shore have yet to be mapped and we hope that these, along with additional outcrop and core studies, will clarify issues about shelf to basin profiles during this important time interval. This new outcrop data will be combined with extensive new digital outcrop data to build a 3D model of this reservoir analog and aquifer system.

This is a comparative study of the origin and stratigraphic architecture of Albian intrashelf basins on the Comanche Shelf, specifically the Maverick and East Texas intrashelf basins. As part of this work Jeff Sitgreaves (Ph.D.) will do digital field mapping and modeling of the uppermost Albian along the Pecos River Canyon that marks both the peak shelf to basin relief and subsequent infill of the Maverick Basin. This study will make use of spectacular outcrops near the mouth of the Pecos River and will employ UAV imaging as well as detailed section measuring and mapping to refine this story.

This Albian intrashelf basin work will also have a subsurface focus, and regional core-log-seismic cross sections will be constructed to connect, compare, and contrast the sedimentologic/stratigraphic evolution of the Maverick and East Texas Basins. The initial challenge will be to normalize the regional stratigraphy, after which contrasts in the evolution of the basins associated with different styles of halokinesis will be targeted. Part of the focus of the Cretaceous platform project is to further develop and test the larger sequence framework
Architecture, Lithofacies, and Pore Networks of Newly Established Lower Cretaceous Carbonate Shelf Margins

The Lower Cretaceous stratigraphic section around the Gulf of Mexico (GOM) contains several well documented carbonate shelf margins, which include the Berriasian Knowles shelf margin, Barremian Sligo shelf margin, and Albian Stuart City Shelf margin. This present investigation documents two additional, lesser known carbonate shelf margins that developed between the Knowles and Sligo shelf margins. The existence of the Calvin and Winn shelf margins were established in 1984 by drilling the deep (17,532 ft) ARCO No. 1 Huffman McNeely wildcat well in Natchitoches Parish in northern Louisiana. Wireline logs and cores define the presence of these shelf margin buildups and regional 2D seismic lines support these conclusions. These shelf margins were not recognized earlier because of the lack of deep wells that penetrated this section. The recognition of these two shelf margins is important as they add to the stratigraphic history and architecture of this deep Lower Cretaceous section and they also may be potential deep-gas, tight-carbonate plays.

The major goal of this investigation is to document the presence of the Calvin and Winn carbonate shelf margins in the north central GOM area. Specific objectives are to (1) map the trend of the Calvin and Winn shelf margins in northern Louisiana and East Texas using several 2D seismic lines, (2) characterize the stratal architecture of the shelf margin in the area of the No. 1 Huffman McNeely well as seen on a 2-D seismic line, (3) define the lithofacies of each unit as seen in core, and (4) present pore networks and associate reservoir quality.

West Caicos—Laboratory for Modeling Embryonic Fracture Systems on Steep-Rimmed Margins and Strandplain Grainstone Depositional Patterns

West Caicos is a grainstone-dominated strandplain accumulation on the west margin of the Caicos Platform that forms an excellent analog for this distinct style of grainstone deposit type. Charlie Kerans, Chris Zahm, Steve Bachtel (Chevron) and new M.Sc. student Nick Danger plan to continue to develop this analog database with the following long-term objectives:

- Further develop foreshore-shoreface strandplain model for carbonate grainstones.
- Understand role of early-formed fractures in strandplain and platform-margin evolution.
- Document role of sea level vs. position on platform and wind directions for strandplain accumulation/preservation.
- Document patterns of early diagenesis (intrabeach-ridge evaporites and associated hydrology).
• Collect airborne lidar (green) on West Caicos Island and surrounding shelf for use in developing a 3D structural/facies/hydrologic/diagenetic model of the island complex.
• Collect bathymetric grid extending westward from key locations along West Caicos to further constrain the margin profile.

In 2014 we completed high-resolution (sub-1m) mapping of the western OIS 5E exposures along the western margin of the island and have a first-pass digitized version of this mapping. Critical additional areas for mapping will be along the southern coast where older units (OIS 7?, 9?) are exposed and provide important information about island evolution. Continuing mapping to the north will be important as well as it will allow us to understand the position of the Pleistocene–Holocene boundary and how that continues around the rest of the island, a surprisingly subtle boundary for an unconformity with a >100ky time gap and 120m eustatic fluctuation. Once lidar is collected and processed we should be able to start the process of defining the rest of the island evolution including the sequence of beach ridge complexes and lake systems.

Significant effort on additional fracture mapping will be made for the southern portion of the island where older strata are exposed. The older strata and fractures will be analyzed with respect to the Boat Cove area to the north where potentially younger fractures have developed in areas overlying older strata and potentially older fractures. Key questions from this research include (1) what role do older fractures play on younger deformation; (2) are fractures that are exposed at Boat Cove related to the present shelf margin configuration or are they a reflection of the south-to-north depositional evolution being investigated by Kerans and Bachtel; and (3) what is the influence of eustatic fluctuations on fracture development and geomorphology of West Caicos.

**EVAPORITE PALEOKARST SYSTEMS**

Through our research relative to karstification of both carbonates and evaporites, we recognize that they form important reservoirs in their own right or modify other reservoirs (e.g., Lower Ordovician throughout the world, Siluro-Devonian and Permian in West Texas, Lower Cretaceous in Mexico and the Western Florida Shelf, Mississippian in the western U.S., Permian in Kazakhstan, etc.). Important features and concepts relative to an understanding of ancient systems include (1) controls on cavern dimensions and resulting products, (2) system and passage morphology, (3) early breakdown/collapse and associated fractures, (4) differentiating far-field stress fractures from cavern-stress-related fractures, (5) sediment-fill types and origins, (6) origin and description of pore networks, (7) rejuvenation of caves (composite cave systems), (8) comparing karst expressions regionally, and (9) integrating results into finite-element models and ultimately understanding this influence on reservoir-flow modeling.
We will summarize concepts related to the stratigraphic and structural architecture and pore networks of evaporite paleokarst based on our studies of evaporite paleokarst outcrops associated with the dissolution of the Kirschberg Evaporites in the Lower Cretaceous Edwards Group near Junction, Texas, work on the Mississippian Madison Group in Wyoming, fieldwork in northern Spain, and a literature survey.

**Collaborative Research Project for Karst and Fracture Characterization and Modeling of Devonian Grosmont**

Complex deformation related to evaporite removal in the Grosmont of the Upper Ireton creates significant reservoir heterogeneity. However, billions of barrels of low-API bitumen are present in the Grosmont, making characterization valuable. The RCRL group will be working with various datasets to both characterize the karst and fracture distribution and develop subsurface reservoir models that are based on well and core data, as well as 3D seismic volumes. It will be a multi-year study. Research results, including modeling strategy and work flow, will be shared with the RCRL sponsors during annual meetings.

**Geomodeling of Karst-Collapse Systems**

Karst-collapse systems have distinct reservoir elements that are extremely heterogeneous, with matrix, fractures, and touching and nontouching vuggy pores. We will construct geomodels that capture these variations within the Cretaceous Kirschberg (greater Junction area) and Mississippian Madison Formations (Bighorn Canyon Recreation area). The geomodels constructed for the karst-collapse systems will include distribution of essential reservoir elements, including matrix and karst-collapse breccias, along with dissolution-enhanced fractures, fracture fills, and deformation-related discrete fractures. We expect nonunique geomodel solutions, but we hope to highlight key elements to reservoir-flow behavior, including pore-volume distribution and recovery and sweep efficiency.

**TERTIARY CARBONATE SYSTEMS**

The RCRL has worked on cores from several Southeast Asia reservoirs. The cores, which are from isolated platforms, cover depositional settings ranging from platform interior, to reef-rim, to deeper-water slope systems of Oligocene to Miocene age. One focus of the research in Tertiary carbonates is to improve depositional models that will cover a wide spectrum of Oligo-Miocene platforms. In 2015, a particular focus will be on improving our understanding of carbonate deposition and stratigraphic architecture in extension-tectonic settings and carbonate deposition and stratigraphic architecture of platforms deposited over highly irregular topography.
Miocene Carbonate Platform in the Mut and Adana Basins, South Turkey

Last year, we started a long term effort (2-5 years) of investigating both the Mut Basin and the Adana basin in south-central Turkey. The Adana Basin was a rapidly subsiding basin in the Neogene, with a small (1–4 km wide) platform developing on the crest of normal fault blocks. Ozen Gurbuz acquired Gigapans and has completed geological mapping on the best exposed fault-controlled, back-stepping platform as part of his M.Sc. thesis. These dataset will be synthesized in 2015 and additional outcrop data and potentially subsurface data will be integrated in the study. In addition, we will tentatively revisit the classic exposure of the Mut Basin to acquire lidar and Gigapan in 2015 in collaboration with Kemal Gurbuz from Cukurova University. The goal is to complement and expend already existing detailed geological study of these exceptionally exposed attached and isolated platforms and potentially ultimately build an updated 3D geocellular model.

Lower Miocene Isolated Platforms in the Java Sea, Indonesia

Reynaldy Fifariz will continue his Ph.D. research, in collaboration with Professor Benjamin Sapiie of ITB Bandung, on the regional architecture and detailed depositional and reservoir model of the various Oligo-Miocene isolated carbonate platforms that grew on a complex horst-and-graben system reactivated by later inversion. These platforms have several reservoir intervals of different ages and present numerous styles of carbonate systems ranging from a mixed carbonate-siliciclastic, clay-rich shelf system to small aggrading coralgal pinnacle reefs.

Tertiary Temperate to Tropical Platform of the NW Shelf of Australia

We have acquired through the Australian government an extensive public seismic dataset that cover a large portion of the NW Australian shelf covering the Carnavon, Canning, Browse, and Bonaparte Basins. The dataset consists of more than 100 3D seismic dataset and an extensive 2D regional grid. These basins have an extensive temperate to subtropical prograding shelf that is overlain by several tropical rimmed shelves. These tropical shelves also have numerous isolated carbonates platforms that are spectacularly imaged in the shallow part of the seismic survey. We are planning to use this exceptional dataset to understand the large scale regional control on the architecture and development of subtropical shelves and tropical rimmed shelves and isolated platforms. In addition, several high-resolution, high-quality 3D seismic datasets will allow us to examine in detail the architecture of the intrashelf tropical isolated platform, as well as the shelf margin using seismic volume interpretation and seismic geomorphology approaches. We are planning to gain valuable insights into the various stratigraphic architectural evolutional sequences of these systems, but also we plan to collect quantified data about various platform architecture attributes (such as shapes, dimensions, slope angle, slope height, P/A ratio, seismic facies proportion, and other parameters).
TIGHT CARBONATE RESERVOIRS

Origin and Petrophysics of Tight Limestone Reservoirs

We see gas production from “tight” carbonate reservoirs as a significant unconventional resource, with important examples including the Lower Cretaceous Stuart City Trend and Sligo Trend in south Texas or many of the Middle East Lower Cretaceous reservoirs. We are now searching for other oil and gas fields that produce from low-permeability limestones to determine whether micropores are major contributors to production. We have so far collected case histories from throughout the stratigraphic column. An important part of this study is investigating and cataloging of micropore/microrhombic calcite reservoirs worldwide. In this project, we have defines the types, origins, temporal and spatial distribution, and petrophysical properties of micropore/microrhombic limestone. 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.

Documentation of Micropore Networks in Dolomites

Most investigations of micropores have been in limestone, but we now recogne that micropores are common in dolomites also. A study of the Leonardian Clear Fork Formation in the Goldsmith field in Ector County, Texas has demonstrated that micropores are common and may affect saturation and reserve estimates. The nanopore to micropore network is associated with overdolomitization, replacement/precipitation processes, and replacement of microrhombs formerly associated with Mg-calcite. Several new case histories will be conducted to further document dolostone related micropore networks, especially how they form and their petrophysical properties.

Develop Paleozoic Case Histories of Carbonate with Well-Developed Micropore Networks

Micropore networks are now well characterized in the Mesozoic and Tertiary sections. We are now collecting and analyzing case histories from Paleozoic units where it appears micropores are extremely common. An investigation of the Pennsylvanian Caddo Limestone in Stephens County, Texas shows a dual pore network of moldic pores (some moldic pores are related to collapsed phylloid algal plates) and micropores developed by the stabilization of Mg-calcite fossils, microbialites, and micrite envelopes. We will search for more case histories of micropore network development in older Paleozoic sections.
Origin of Micropores in Coccolith-Rich Muds (Chalks)

We are investigating the occurrence of micropores in chalks and how they evolve with burial. They are deposited with high porosities, and they lose much of this porosity by mechanical compaction. Diagenesis associated with burial (time, temperature, and pressure) consists of calcite overgrowths on coccolith plates, and fragments reduce porosity further. We have started on a sample set of carbonated muds (some argillaceous) from outcrops west of Del Rio, Texas. These include Upper Cretaceous Buda, Eagle Ford, and Austin Chalk units. We are now analyzing subsurface datasets from the Buda, Eagle Ford, Austin, and Annona/Ozan chalks in the GOM, as well as the Niobrara Chalk in Colorado. We plan to collect more petrophysical data on these chalks and relate reservoir quality to grain size and sorting.

Origin of Micrite and Associated Micropores

The origin of porosity in mud-dominated fabrics remains a controversial issue. RCRL studies have demonstrated that nano-sized particles of aragonite/calcite depositional mud convert to micro-size micrite crystals without loss of porosity. Reduction of porosity occurs with burial compaction and cementation. However, many authors concluded that dissolution plays an important role in the formation of the microporous micrite reservoirs.

In 2015 we will continue to investigate the criteria used to argue for dissolution by studying the origin of the micrite crystals. Crystal shape is commonly presented as evidence of dissolution; euhedral vs. anhedral crystals. Current research suggests that the typical 2-micron micrite crystal was formed by cementing several nano-sized crystals together with associated calcite overgrowths resulting in an anhedral crystal. Aragonite needles are dissolved because they are diagenetically unstable and the dissolved carbonate is utilized locally as cement. The smallest calcite crystals are also dissolved by Ostwald ripening and the dissolved carbonate then precipitated as cement. Dissolution is not responsible for the porosity.

Early Development of Micropore Networks

Our research on micropore formation has endeavored to define the paragenetic history associated with the development to micropores. We have investigated shallow buried (low maturity) chalks, the aragonite mud to calcite microrhomb transition, and modern skeletal grains to understand the evolution of micropores. We still need to collect data on early Recent and Pleistocene strata to document the early, low- maturity stages of micropore development. Suitable areas of collection of samples are being considered.
Petrophysics of Micropores

Micropores are present in almost all limestone reservoirs. Petrophysical properties of microporous mud-dominated fabrics are generally predictable. Predicting the petrophysical properties of grain-dominate fabrics, however, is more difficult. Permeability tends to be controlled by intergrain porosity and the reservoir problem is to determine the intergrain porosity. However, when intergrain pores space is filled with cement the permeability is determined by the characteristics of the intragrain micropores and how they are connected to form a pore network.

In 2015, we will continue to investigate the petrophysics and origin of microporous cement grain-dominated fabrics in the Word field, South Texas. Grain-dominated fabrics with only intragrain micropores are of special interest. The intergrain pores have been infilled with calcite cement and the only pore space is within the grains. Here the generalization that permeability is a function of intergrain porosity is not correct. These fabrics commonly have permeability values as high as 2 md and are found in other Cretaceous gas fields. The relationship of permeability to porosity, pore-throat size, crystal size, and pore-space distribution will be emphasized.

MicroCT-Scan Analysis of Micropores in Carbonates

We are initiating a new research effort where we will microCT scan 1-mm plugs of microporous carbonates. The 3D scans will be analyzed using FEI Avizo Beta 9.0 software that allows us to calculate permeability in multiple directions, simulate flow, outline in 3D pore network, and define continuity of pore flow paths.

Quantification of Micropores within a Dual Pore Network

We are in the process of 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.

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.

**CARBONATE MATERIAL PROPERTIES AND GEOMECHANICS**

Research on carbonate material properties, differential compaction, and fracture modeling will be a significant contribution in the 2015 RCRL research program. Previous research efforts have emphasized high-resolution collection of rock properties in different carbonate systems. In 2015 we are expanding this effort to better understand what the critical properties are in numerous carbonate systems and applications. Critical questions to be addressed in our short- and long-term goals are:

1. Do facies characteristics (fabric, texture, mineralogy, etc) control elastic properties in carbonate?
2. To what extent can we link mechanical properties to facies and thus be predictive?
3. What is the distribution and level of heterogeneity of each elastic property within a single facies?
4. What controls heterogeneity of mechanical properties?
5. What are the implications for reservoir characterization?
6. Can we confidently invert relevant elastic parameters at the seismic scale?

In addition to these specified interests, we are expanding our research to understand the importance of these rock properties on compaction, collapse, and subsequent fracture development by incorporating finite-element modeling of materials and deformation using the Elfen code. Key research topics within this theme in 2015 include:
(1) Differential compaction and fracturing on the flanks of mounds in the Sacramento Mountains with potential application to flank fracture development within the Northern SACROC unit;

(2) Early-formed fractures in steep-rimmed shelf margin systems (i.e., Guadalupian and Pleistocene at West Caicos);

(3) Mechanical stratigraphy modeling in weak-strong layered rocks systems (e.g., Niobrara Chalk) and the influence of layer-parallel slip at these contacts in fracture development;

(4) Fracture development in karst collapse systems, including the role of variable mechanical properties in the deformed strata.

The common tie for each of these research questions is the ability to collect rock properties and geomaterials that accurately represents the strata within each of these systems. This is an ambitious and long-term project, but one that we feel we are uniquely qualified to pursue with our integrated research group.

**TOPICAL STUDIES**

**Lidar-Orthogrammetry Fusion and Drone Acquisition**

How to optimally integrate the various digital acquisitions of outcrop data into a common dataset remains an evolving research topic for the RCRL. We are still refining our workflow for the acquisition of high-resolution orthographic acquisition using aerial drones, especially optimizing parameter such as light altitude, percentage of overlap between photos, camera resolution, shooting angle, and flight plan to produce reliable digital outcrop model in various terrain configuration (pavement, cliff, combination of the two). In 2015, we hope to increase the efficiency and accuracy of the aerial acquisition by implementing autonomous flight control (e.g., pre-programmed GPS-controlled flight-path as opposed to manual control of the UAV).

**Integrated Facies, Fracture, and Reservoir Model of SACROC**

The RCRL group has been working on various aspects of SACROC field over the last decade. Next year, we will try to integrate all the different studies that we have performed on this isolated Upper Carboniferous platform into a single reservoir model. Several challenges in the SACROC field make it an ideal, yet challenging, dataset for building a reservoir model. Sacroc geomodeling will be expanded in 2015 to include a reassessment of the geomodel with the goal of integrating cycle-scale depositional facies and diagenetic overprints to predict matrix reservoir
properties. The focus will be on the Canyon section but aspects of the late dolomite overprint in the Cisco will also be important.

**Isotopic and Elemental Approaches to Carbonate Stratigraphy, Depositional Settings, and Diagenesis**

A concerted effort to develop the links between isotopic and elemental chemistry of carbonate and mixed carbonate/siliciclastic reservoirs is under way. This work currently encompasses work on many Cretaceous units from the Austin Chalk; Eagle Ford/Boquillas, Buda, Salmon Peak, Stuart City, and Pearsall strata in Texas; the Sunniland Formation in Florida; and the Niobrara in Colorado. Four portable X-ray fluorescence units, a microbeam X-ray fluorescence unit, and a rapid-analysis X-ray diffractometer are the instruments that we use to develop geochemical, microgeochemical, and mineralogical datasets, respectively, for the just-mentioned reservoirs. Over the next 4 months, a stable isotope laboratory devoted to analysis of δ^{13}C/δ^{18}O of carbonates and δ^{13}C/δ^{15}N of rock organics will be built at the BEG. The geochemical datasets will most likely be utilized not only for chemostratigraphic control, but also to arrive at a deeper understanding of depositional and postdepositional conditions. Harry Rowe will focus on developing geochemically based models that complement ongoing work and help to expand the understanding of paleoceanographic setting and diagenetic history. An additional goal is development of reference-material suites that will better underpin the elemental analysis of evaporite paleokarst and redox-sensitive metals in diagenetic carbonates. The first reference suite that includes Austin, Buda, Edwards, and Georgetown will be developed.

**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. We have a multifaceted research program that covers (1) carbonate outcrop-reservoir analogs, (2) integrated subsurface carbonate-reservoir characterization, and (3) geomodeling and geologically realistic modeling of seismic, karst, and fractures. Research members of the RCRL group have had extensive industry experience or have been working closely with industry to solve reservoir characterization problems. We strive to incorporate the latest technology and concepts toward development of the “best practice” approach to integrated reservoir characterization.

In 2015, 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


Mahmoud Al-Nazaghah, Ph.D. Aspirant (expected completion, May 2017) – Research objectives: Origin and architecture of glacioeustatically forced reservoir flow units, SACROC field and equivalent outcrop datasets, Co-supervisors, Charlie Kerans, Xavier Janson, and Chris Zahm; Committee: Not yet selected.


Reynaldy Fifariz, Ph.D. Candidate (expected completion, May 2016) – 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. Title of thesis: Regional Stratigraphic Architecture and Depositional Model of Miocene Carbonate, East Java, Indonesia; Co-supervisors: X. Janson and C. Kerans; Committee: Ron Steel, Graig Fulthorp, and Ben Sapiie.


Ahmed Hassan, Ph.D. Candidate (expected completion May, 2016) – Research objectives: Distribution of intragranular micropores in a low-resistivity pay zone from Lower Cretaceous Thamama Group, Abu Dhabi, United Arab Emirate. Title of thesis: Factors Controlling Dual Porosity Networks in Low-Resistivity Pay Carbonates from Lower Cretaceous Thamama Group, Abu Dhabi, United Arab Emirates; Co-supervisor: C. Kerans and R. Loucks; Committee: Not yet selected.

Chris Hendricks, M.Sc. Candidate (Joint student between RCRL and STARR; expected completion, Aug 2016) – Research objectives: Depositional setting, lithofacies, and chronostratigraphy of the Buda and Austin Chalk intervals in south Texas using core-based XRF data.; Supervisors: H. Rowe and R. Loucks; Committee: Not yet selected.
Gregory Hurd, Ph.D. Candidate (expected completion, May 2016) –Research objective: Interpreting and modeling processes of deposition and deformation on carbonate slopes. Title of thesis: Not yet selected; Co-supervisors: C. Kerans and X. Janson; Committee: P. Flemings, D. Mohrig, and T. Simo.


Maren Mathisen, M.Sc. Candidate (expected completion, December 2014) –Research objectives: Characterizing the fault and fracture system between Rattlesnake and Slaughter Canyons and integrating with previous work in the Walnut and Dark Canyons toward an understanding of the structural variability along a change in strike of the Capitan shelf margin. Title of thesis: Structural Evolution along a Strike Change in the Capitan Shelf Margin, Guadalupe Mountains, SE New Mexico; Co-supervisors: C. Zahm and C. Kerans; Committee: not yet selected.

Kyle McKenzie, M.Sc. Candidate (Joint student between RCRL and STARR; expected completion, Aug 2016) –Research objectives: Regional architecture, lithofacies, and regional heterogeneity of the Lower Glen Rose section in the outcrops of the Lake Travis area and subsurface cores in the Frio County area in Texas. Emphasis will be on the environmental recovery from the Pearsall OAE events and on lateral heterogeneity of potential reservoir facies. Supervisors: C. Kerans and R. Loucks; Committee: Not yet selected.


Jeff Sitgreaves, Ph.D. Aspirant, (expected completion Fall, 2016) –Research objectives: Evolution and origin of Cretaceous intrashelf basins in NW Gulf of Mexico, including Maverick and East Texas basins), thesis will combine extensive regional subsurface mapping and correlation using core, logs, and seismic data, and digital outcrop mapping of Maverick intrashelf basin margin in southernmost exposures of Pecos River Canyon: Title of thesis – not yet selected. Co-supervisors: Charlie Kerans and Bob Loucks; Committee: Not yet selected.


**Recently Graduated**


APPENDIX B: RECENT RCRL PUBLICATIONS

2014


Phelps, Ryan M., Charles Kerans, Jason Jeremiah, Rui O Da-Gama, David Hull, and Robert G. Loucks, in review, Response and recovery of the Comanche carbonate platform surrounding multiple Cretaceous Oceanic Anoxic Events, northern Gulf of Mexico, 157 ms pgs.


2013


26


2011


Janson, X., Eberli, G. P., Lomando, A. J., and Bonnaffe, F., 2011, Seismic characterization of large-scale platform-margin collapse along the Zhujiang carbonate platform (Miocene) of the South China Sea, based on Miocene outcrop analogs from Mut Basin, Turkey: SEPM (Society for Sedimentary Geology) Special Publication No. 95, p. 79-98.


2010


2009

