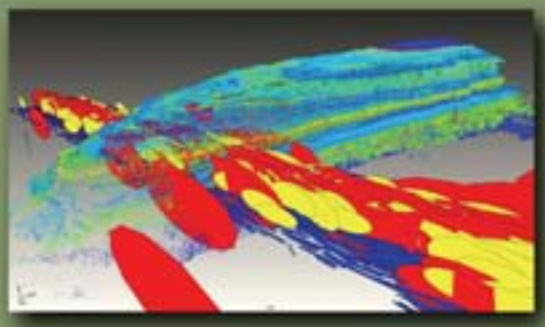
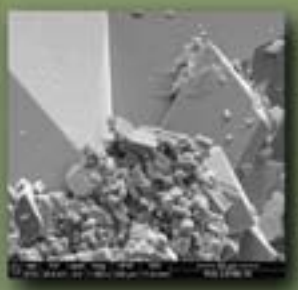
Reservoir Characterization Research Laboratory
for Carbonate Studies

Executive Summary and Prospectus for 2011

Charles Kerans and Robert Loucks: Co-Principal Investigators





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Reservoir Characterization Research Laboratory for Carbonate Studies

Research Plans for 2011

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

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Reservoir Characterization Research Laboratory Research Plans for 2011

Figure

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Reservoir Characterization Research Laboratory

Research Plans for 2011

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, 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 2011. A list of sponsors during 2009 and 2010 are presented in Table 1. In 2011 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 (2011 and 2012) rate of $50,000 per year. The agreement would be such that an 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 and has produced numerous external publications, as well as BEG publications, on carbonate reservoir characterization, sequence stratigraphy, petrophysics, geostatistics, and petroleum engineering, maintaining strong company sponsorship each year (Table 1). 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 strong 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. Marc-Olivier Titeux, Postdoc, Geological Engineer
Reservoir Engineer (in the process of searching)
Mr. Joseph El-Azzi, Research Scientist Associate, Geologist

Associate Staff

Dr. Steve Ruppel, Senior Research Scientist, Geologist
Dr. Hongliu Zeng, Research Scientist, Geophysicist
Ms. Laura Zahm, Research Scientist Associate, Geologist

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 student assistants, who have included several award-winning students, many of who are now working in industry.

Table 1. RCRL Sponsors 2009/2010

2009	2010
Anadarko Petroleum Corporation	Anadarko Petroleum Corporation
BGP (China National Petroleum Corp.)	BHP Billiton
BHP Billiton	BP
BP	Chevron
Chevron	ConocoPhillips
ConocoPhillips	ExxonMobil
ENI	Husky
ExxonMobil	JAPEX
JAPEX	KinderMorgan
KinderMorgan	Oxy Permian
Marathon Oil Corporation	Petrobras
Oxy Permian	Pioneer Natural Resources
Petrobras	Saudi Aramco
Pioneer Natural Resources	Shell
Saudi Aramco	Statoil-Hydro
Shell	Suncor Energy
Statoil-Hydro	Whiting Petroleum Corporation
Whiting Petroleum Corporation	

RCRL RESEARCH PROSPECTUS FOR 2011

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 that have been developed out of our experience and feedback from our sponsorship are summarized in Figure 1. The research themes, similar to those of subsurface characterization, are composed of linked and overlapping areas of interest. For each topic, we have listed one or two RCRL members as the primary contact for a topic; however, questions can be addressed to any member of the group.

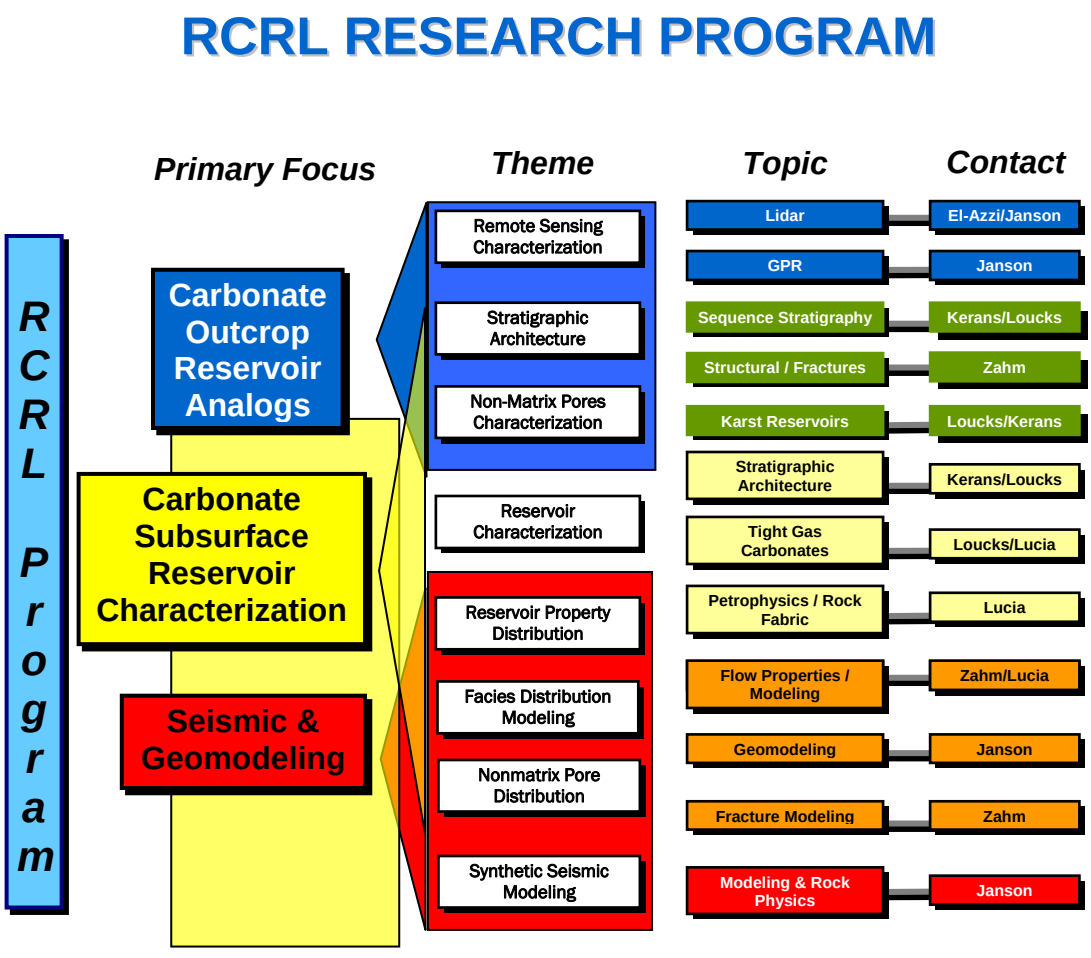

Figure 1. The RCRL Research Program integration of overlapping themes.

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. In addition, PDF files of papers and preprints authored by our group are available.

Workshops and Field Courses

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. We will be offering a field seminar in the spring of 2011 highlighting stratigraphic variability and associated deformation in greenhouse, icehouse, and transition climates observed in West Texas and New Mexico Paleozoic systems.

We will also be offering a classroom seminar in 2011. It will be an updated version of the popular characterization course that RCRL has conducted in the past that will cover procedures for carbonate reservoir modeling. New insights from geophysics and fracture prediction will be incorporated into this workshop.

We will send a more detailed program of field trips and workshops early in 2011.

Interaction with RCRL

RCRL makes a concerted effort to interact with sponsors during the year through concentrated topical discussions and short-term projects with specific companies to help transfer of research results into an industrial workflow. During 2010 we visited BP in

Britain and presented seminars on karst geology and another on Nummulite deposits of Tunisia. We also visited Shell in The Hague and presented lectures on evaporite and karst systems. Another short seminar was held at BHP in Houston on Miocene carbonates. We led a special field trip for Shell to Central Texas to review outcrops of evaporite paleokarst. We have participated in company reviews such as the Chevron Subsurface Characterization Forum as a way of introducing our research throughout a company. A number of discussions on micropores have taken place with several companies. There have been many interactions, and these are just a few of them.

Also, over the last few years we have collaborated with (1) Whiting Petroleum Corporation on Keystone field in West Texas, (2) Pioneer Natural Resources on the Stuart City Trend in South Texas, (3) BGP on the karsted Ordovician section in the Tarim Basin in western China, (4) ExxonMobil on outcrops in Indonesia for Southeast Asia reservoir analogs, (5) Saudi Aramco on Ghawar field, and (6) Petrobras on integrated fractured reservoir characterization of Albian carbonates. Each of these projects addresses company needs and will lead to results that will aid field development, as well as provide research data for developing new concepts. We encourage sponsors to contact us with projects that could be mutually beneficial to that company and to the broader RCRL membership.

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. 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, and Bob Loucks all have taught courses in the Jackson School, and several of them are on the Graduate Studies Committee. The students obtain comprehensive training in carbonates working on RCRL projects and interacting with RCRL professional staff. Each of the students 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 2011

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 wide 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, karst, and fractures. In the 23 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), 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, five thematic areas encompass the expertise of the consortium: (1) remote-sensing characterization (e.g., lidar and ground-penetrating radar), (2) geologic framework development (e.g., stratigraphic and structural architecture), (3) nonmatrix pore characterization (e.g., fractures and karst cavities and vugs), (4) reservoir characterization (e.g., identification and distribution of relevant properties important to enhanced hydrocarbon recovery), and (5) analog-based synthetic seismic and geomodeling of facies, fractures, and karst. For 2011, we are focusing research on projects that (1) have multiple levels of integration within our themes, (2) maximize the abilities and experience of our research group, and (3) have the potential to make the greatest impact on fundamental understanding of the carbonate reservoir system. With these challenges in mind, we have selected outcrop and subsurface studies that specifically address hydrocarbon recovery issues important to our sponsors.

CARBONATE OUTCROP RESERVOIR ANALOGS

RCRL is known for its research in developing carbonate outcrop reservoir analogs in both Paleozoic and Mesozoic strata. We are refining concepts and tools to enhance this endeavor, such as geobody dimensional data within a sequence framework, sequence-linked bedding attributes and mechanical stratigraphy, and 3D quantitative geomodeling using ground-based and airborne lidar data. A recent data-collection highlight of the

RCRL program was acquisition of an extensive airborne lidar dataset over a large part of the Guadalupe Mountains, a classic area of carbonate research. We are also focusing on how karst systems vary (both carbonate and evaporite) and on structural reservoir components such as fractures, faults, and nonmatrix pore systems.

Airborne Lidar-Assisted Regional Framework of the Guadalupe Mountains

Emphasis on outcrop analog research in 2010 focused on Cretaceous platform carbonates and evaporite paleokarst systems, both in the Cretaceous of Central Texas and the Mississippian of the Rockies. The main progress in 2010 regarding the RCRL's research using airborne lidar was associated with Harman's stratigraphic architecture work on the Yates HFS of Slaughter Canyon. Thus, although theme 2 remains intact and will move forward, emphasis will be placed on synthesis work (theme 1) and on a revised theme 3, which will look at shelf-margin and slope systems of the upper Yates and Tansill Formations in a series of canyons from Dark Canyon in the north through Big Canyon in the southwest.

Major themes for 2011 research in the Guadalupe Mountains will be

1. Regional synthesis of Seven Rivers through Tansill intervals and associated reef-margin and slope strata (Kerans et al.). This synthesis will involve mapping of selected key surfaces using the data volume through the main canyons of Guadalupe and Carlsbad Caverns National Parks, as well as relevant national forest areas.
2. Detailed mapping and stratigraphic interpretation of the Yates framework from McKittrick through Slaughter Canyons (Kerans, Harman, and work by Resor and students, plus previously published work by Hunt et al.). This work will focus on the high-frequency sequence framework of the Yates as initially set up by Tinker (1998) and Osleger (1998), quantifying sequence architecture, facies tract widths, and facies partitioning within these sequences.
3. Linkage of shelf-margin and slope systems and the role of early syndepositional fracture systems in platform-margin development is theme 3. The response of carbonate platform-margin and slope facies to major episodes of base-level fall has remained controversial, particularly when the marginal facies are dominated by microbial carbonates that may be less sensitive to eustatic shifts. Work by Hunt, Fitchen, and Kosa illustrates the importance of syndepositional fractures in Yates shelf strata in Slaughter Canyon. More recently Rush, as part of the RCRL program, documented shelf-margin collapse in the Tansill/Capitan margin at Walnut Canyon, and Frost, Budd, and Kerans have focused on syndepositional fracturing and diagenesis within a stratigraphic context in Tansill carbonates of Dark Canyon. Reconnaissance work in Slaughter Canyon, coupled with observations in airborne lidar, suggests that major syndepositional fractures within the reef margin/slope are more important than previously recognized, and we plan to test this supposition through both field work and digital mapping.

Carbonate and Evaporite Karst Outcrop Analogs

As we continue our research relative to karstification of both carbonates and evaporites, we are recognizing that they form important reservoirs in their own right or modify other reservoirs (Lower Ordovician throughout the world, Siluro-Devonian and Permian in West Texas, Lower Cretaceous in Mexico, Mississippian in the western U.S., Permian in Kazakhstan, etc.). Karst systems evolve with depth, as shown by several authors (e.g., Kerans, 1988, 1989, 1990; Wilson et al., 1992; Loucks 1999). Evolution with depth affects the pore network structure of the reservoir system, as well as the morphology of the original cave system (Loucks, 1999).

Several suggested general origins for the development of karst systems are recognized, with the two end members being epigenic karst originating from the surface by meteoric waters and hypogenic karst originating from a variety of fluids derived in the subsurface. Currently there is much controversy over recognizing these two karst systems in both present and ancient times. In the latter, separating carbonate karst and evaporite karst from one another continues to be difficult because they can form similar breccia and pore networks.

Important features and concepts relative to an understanding of ancient systems include (1) controls on cave dimensions and resulting products, (2) system and passage morphology, (3) early breakdown/collapse and associated fractures, (4) differentiating far-field stress fractures from cave-stress-related fractures, (5) sediment-fill types and origins, (6) origin of pore networks, (7) rejuvenation of caves (composite cave systems), (8) comparing karst expressions regionally, and (9) integrating results into reservoir-flow modeling.

We maintain that a need exists to document a range of Tertiary to Holocene karst systems (with the goal of understanding ancient buried and collapsed systems) that are still active and accessible at the surface. These can include carbonate systems such as Blanchard Spring Cavern in northern Arkansas (long-age-ranging composite cave system [~60 m.y.]) and/or Longhorn Caverns in Texas (both Blanchard and Longhorn systems are epigenetic meteoric caves) and Sonora Caverns and Carlsbad Caverns in West Texas (postulated to be hypogenic caves). Other systems, such as flank margin caves in the Caribbean, could be looked at later.

An ancient karst system can be viewed in a number of outcrops. Evaporite karst and collapsed systems can be investigated in the Triassic to Tertiary section in northeast Spain, in Lower Cretaceous outcrops along I-10 in central West Texas, in outcrops of the Mississippian Madison Formation in Wyoming, in outcrops of the Permian Castile Evaporite in New Mexico, and in the Seven Rivers section in the Rocky Arroyo, New Mexico. Carbonate karst has been studied by members of our group in outcrops of the Franklin Mountains and in quarries, along with associated cores and GPR data from Marble Falls in Central Texas.

We are completing a detailed investigation of evaporite paleokarst in a series of roadcuts (over 80 miles) near Junction, Texas, in the Lower Cretaceous Edwards Group. This area is an excellent analog for an evaporite karst system that did not have a superficial sediment source to fill caverns. As a result, the cavern had little internal sediment fill to support the ceiling. Extensive cavern collapse occurred with associated brecciation and extensive suprastratal deformation.

The Mississippian Madison Formation exhibits an impressive spectrum of dissolution and karst collapse associated with both carbonates and evaporites that has been well documented within the overall sequence stratigraphic architecture by Sonnenfeld (1996). We are in the middle of a major program to study outcrops from Wyoming and southern Montana to provide insight into the evolution of a combined epigenic and evaporite-removal paleokarst developed below a tectonically enhanced second-order supersequence boundary. Paleokarst development varies from systematic solution-enhanced fractures to widespread, laterally extensive evaporite dissolution that is stratigraphically continuous over tens of miles. The role of fractures in the development of vertical dissolution columns has been hypothesized; however, the tectonic and structural controls on fracture development have not been determined. In 2011 we will build on the growing lidar database of the Madison Sequence IV paleokarst system, as well as improving our understanding and characterization of the origins and evolution of the karst development within the Upper Madison section. This work will include spatial mapping of observed karsted zones, breccias, and sediment fill. Results and findings from ongoing research will be delivered at the 2011 RCRL Annual Meeting during a 4-day field trip across Wyoming and into Montana.

Aptian-Albian Ramp-Margin Architecture, Chihuahua Trough/Bisbee Basin

The emphasis on work in the Mural carbonates for 2011 will be to incorporate additional detail into the framework developed by Aisner in 2010 in the Bisbee area. Current border issues are likely to keep our group out of Cabulona, Mexico in 2011. However, several key outcrops in Arizona that were not part of this year's work will be targeted. In particular, new access to the Grassy Hill sections now granted by Freeport McMoran will make it easier to add control and develop a clearer understanding of the distribution of grain-dominated skeletal and oolitic facies in the platform interior. In the Paul's Spur area, several adjacent outcrops and a major quarry immediately to the south of the main reefal exposures will add control to this setting and help in quantifying buildup distribution and lateral continuity of reservoir-analog facies.

Integration of Fracture Systems into Carbonate Sequence Stratigraphic Frameworks

Carbonate sequence stratigraphy provides a framework that enables an improved predictive fracture distribution in the outcrop and subsurface reservoirs. Characterization of relative bed thickness, lithofacies, rock strength, and other rock properties will be linked to the larger sequence stratigraphic architecture, providing additional information

about the distribution of fracture-prone facies. In 2011 we will complete the fracture model for Lewis Canyon and deliver a complete geomodel and fracture characterization of the ramp-crest Albian systems.

The second area of focused research will be within the mixed siliciclastic-carbonate fault-damage zone of the upper Leonardian 6 cycles in the Brokeoff Mountains. This seismically resolvable fault system provides a unique look at variations in fault-damage-zone response between siliciclastics and carbonates (dolostones). The HB section of Fitchen (1988) highlights cyclic sandstone-dolostone algal laminite cycles of the upper L6. We intend to document facies and stratigraphic elements in detail, along with fault-gouge characterization and fracture-development response. This same system of faults can be traced and characterized in at least five other localities along the fault trace, providing an unparalleled expression of fault-fracture development in the Lower San Andres Formation. Characterization will involve ground-based lidar acquisition; RTK-GPS mapping of sections, contacts, and fractures; and significant sample collection for petrographic and rock-strength analyses.

CARBONATE SUBSURFACE RESERVOIR CHARACTERIZATION

RCRL is internationally recognized for its research over the past 23 years in developing basic geological and engineering concepts for reservoir characterization and modeling. The workflow developed by our group impacts the approach used by many companies. To maintain our skill level and to continue to develop new concepts and techniques, we are continuing our work on selected carbonate reservoirs, which will lead to new insights. We are planning to initiate or continue reservoir characterization on several reservoirs that are discussed next. We also have selected several reservoir problems on which to concentrate, including capillary-pressure analysis, micropores, and initial pore structure and associated porosity in modern carbonate allochems.

Integrated Reservoir Characterization Research

Albian Fractured Carbonates, Jabuti Structure, Marlim Leste Field, Offshore Brazil

Ongoing work with Petrobras and iReservoir has led to an established workflow for fractured reservoir characterization, with appropriate emphasis on the role of sequence stratigraphy and rock properties in the characterization process. However, 2011 will also demonstrate innovative methods of incorporating seismic attributes, petrophysics, rock-strength measurements, and outcrop-analog observations of fault-damage zones into advanced fracture reservoir modeling. We will also be investigating the appropriate level of characterization necessary to describe reservoir-flow behavior within a dual-permeability system. The Petrobras project will be completed in spring 2011, with highlights and workflows delivered at the fall 2011 RCRL Annual Meeting.

Albian Carbonates of the Stuart City Margin and Maverick Basin

The Cretaceous (Albian) Stuart City Margin of the south Texas part of the Gulf of Mexico is currently an active area of horizontal-well gas production from low-permeability carbonate packstones and grainstones. Pioneer Natural Resources USA has led exploration and development in this area and has collected extensive fundamental data on these reservoirs. RCRL is working with PNR on Pawnee field, as well as regionally within this shelf-margin Cretaceous trend, to better understand the role of the regional sequence stratigraphic setting (Ryan Phelps' Ph.D. research w/Kerans), fracture systems (Chris Zahm), and microporosity (Loucks and Lucia) in controlling reservoir quality and producibility.

Topical Subsurface Studies

Origin and Petrophysics of Microporous Limestone Reservoirs

Grainstones with intragrain micropores have long been a problem in estimating permeability and water saturation. Recently our Stuart City study described the importance of micropores in low-permeability carbonate gas reservoirs, which is a new finding. We see gas production from "tight" carbonate reservoirs as a possibly significant *unconventional* resource. We intend to search for other gas fields that produce from low-permeability carbonate and determine whether micropores are major contributors to production. An important part of this study is the investigating and cataloging of micropore/microrhombic calcite reservoirs worldwide. In this project we want to define the types, origins, temporal and spatial distribution, and petrophysical properties of micropore/microrhombic calcite.

Our study of the Stuart City shows the importance of microrhombic calcite as the host for micropores. Research questions to be answered cluster around (1) the origin of microrhombic calcite and (2) the petrophysics of carbonates in which micropores are the dominate pore type. Our approach to understanding the origin of microrhombic calcite is to investigate the mineralogy, structure, and porosity of modern skeletons and to study material in transition between modern sediments and microrhombic carbonates. Research questions include (1) What is the evolution of depositional micropores in calcite allochems and mud with burial diagenesis? (2) Does the original pore network in micropore-rich allochems control or affect diagenetically produced microrhombic calcite and associated micropores? (3) What effect does mineralogy have on formation of microrhombic calcite?

A major thrust of our research on micropore limestone reservoirs is to understand the relationship of porosity to permeability and how this pore network affects saturation profiles. Our study of the Stuart City suggests that permeability is primarily related to pore-throat size, with porosity as a minor contributor. In addition, the rock fabric appears to have little effect on permeability or porosity. To build a permeability model, we will use measurements of porosity, permeability, and pore-throat size (from MICP data), together with rock-fabric descriptions from as many reservoirs as possible.

Tertiary Carbonate Systems

A series of cores from several Southeast Asian reservoirs will be analyzed for stratigraphic architecture, depositional environments, lithofacies, and pore networks as a way to initiate a program in Tertiary carbonates. The cores cover depositional settings ranging from reef-rimmed, isolated platforms to deep-water systems in the Oligocene to Miocene sections. An effort will be made to obtain associated wireline-log suites and seismic data. Major objectives are to develop updated models for linking facies associations and stratigraphic architecture to reservoir-pore-network evolution, with a special emphasis on micropore development. Also, several field areas are being considered for outcrop analog research.

Geomechanical Modeling for Fracture-Distribution Prediction, Karst-Collapse Systems

As mentioned earlier, paleokarst systems produce economically viable hydrocarbon reservoirs and aquifers. For instance, Yates field in West Texas, Permian Basin, has produced 1.2 Bbbl of oil from an estimated OOIP of 4 Bbbl (Craig, 1990). In China, estimated reserves in Jingbian field are 25 Bbbl (Li et al., 2008), whereas in North America, the Devonian carbonate reservoirs in Alberta show a large potential in heavy oil production, owing to dissolution of the evaporitic Hondo Formation (Huebscher, 1996) in the Grosmont carbonate section. Characterization of such geobodies, performed for reservoir simulation, must include the typical sediment architecture and facies properties most commonly observed within collapsed paleocaves. Flow simulations in these paleocaves are impacted by extent and topology of the cave systems, as well as by distribution of collapse-related facies or breccias and petrological properties of their embedded rocks. Thus, fracture networks that result from collapse of cave passages are at a premium for any subsequent flow within this environment—be it from aquifer settings or hydrocarbon reservoirs. Sensitivity analysis of the fracture networks is necessary for elaboration of a strategy to predict such reservoir properties.

To improve accuracy of the static reservoir model, we are developing numerical simulations of cave collapse to study the architecture and reservoir properties of paleokarst carbonates. The objective of this study is to perform a mechanical analysis of collapsed-stratal patterns within carbonate paleocaves using a continuum/discrete-modeling approach. Through the use collapsed-cave models, we are predicting comparable fracture distributions with natural karst systems. We aim at providing an analysis of simulated collapse using an outcrop example located in Mallorca Island (Spain). Also, a sensitivity analysis will help constrain fracture distributions and subsequent flow properties regarding specific key parameters used in dedicated reservoir modeling.

SYNTHETIC SEISMIC MODELING, GEOMODELING, MODELING OF MATRIX AND NONMATRIX PORE SYSTEMS, AND ROCK-STRENGTH CHARACTERIZATION

With its extensive experience developing outcrop and subsurface analogs, the RCRL team continues to focus on ensuring that geologically realistic models are developed that adequately capture the properties relevant to subsurface reservoirs. The catalog of outcrops that have been analyzed at a meaningful scale for reservoir characterization is notable. An important and ever-present challenge is to develop methods of representing these realistic images of reservoir property heterogeneity in subsurface models. Toward this end, research is ongoing in synthetic seismic modeling of reservoir analogs and improving the application of multipoint statistics in defining both facies and karst distribution.

Modeling Carbonate Systems Using Multipoint Statistics

Collaborative research between RCRL and Dr. Sanjay Srinivasan of UT Petroleum and Geosystems Engineering is investigating the application of multipoint statistical (MPS) modeling to numerous aspects of carbonate systems and reservoir modeling. The strength of multipoint statistics is that it is based on pattern recognition that uses geologically based training images rather than traditional pixel-based variograms. We are aiming to integrate more a priori geological knowledge into this geostatistical technique by constructing both statistically and geologically meaningful training images for a range of carbonate stratigraphic architectures and other heterogeneities common to carbonate systems (e.g., fractures and karst). Our goal is to develop algorithms and workflows that combine geostatistics and deterministic approaches to improve our ability to model carbonate systems in subsurface reservoirs. We are currently investigating how MPS might be used to model karst and other nonmatrix pore systems for improved distribution of these heterogeneities in subsurface reservoir models. Our initial research is focusing on two examples—paleokarst development in Yates field of West Texas and outcrop and subsurface examples from the Mississippian Madison Formation of northern Wyoming. Paleokarst systems are seldom a primary target of exploration or production, and few examples illustrate karst features being interpreted as the main reservoir. Karst features such as caves, sinkholes, and tower karst have a high degree of spatial variability and are challenging to reproduce realistically in 3D, let alone to condition statistics to subsurface data (e.g., well logs, core, pressure tests, history matches, or seismic attributes). Our approach consists of gathering representative statistics of paleokarst elements such as solution-widened cavity systems, collapse-breccia complexes, and suprastratal deformation zones from selected outcrop and subsurface datasets. Because fully 3D paleokarst data are limited, we also plan to analyze modern karst features. A stepwise approach for this modeling involves

1. Investigating the mechanics of collapsing voids and resulting increased fracture intensity,
2. Developing training images for selected karst and paleokarst systems,

3. Modifying these images to honor local and regional structural framework,
4. Scanning the training image to extract relevant spatial patterns, and
5. Simulating karst/paleokarst patterns on the basis of statistics from the training image and conditioning the model to known outcrop or subsurface data.

In 2011, Selin Erzeybek's (Ph.D. candidate) dissertation will focus on applying the newly developed MPS algorithm to model paleokarst in the Yates field from which a full dataset was provided by Kinder Morgan.

Spatial Distribution of Seismic Properties in Carbonate Rocks

This research project proposes to investigate vertical and lateral seismic velocity heterogeneity in carbonate rocks. We have recently collected an extensive set of velocity data in the grainstone cycle in Lawyer Canyon. This is the area where we have previously collected detailed porosity and permeability data that were used to analyze the scale of petrophysical heterogeneities (Jennings et al., 1998). We will follow a similar acquisition and processing workflow to compare scale and style of heterogeneity between these two rock properties that are difficult to relate. The goal of this study is not only to examine the potential covariance between seismic velocity and other petrophysical characteristics, but also to investigate the amount of small-scale heterogeneity that needs to be modeled in our synthetic experiment to render natural properties variation adequately. In 2011, we will continue analyzing the dataset acquire in 2010. Our goals for this year is to build upon last year analysis by tying the velocity measurement to petrophysical data and investigate the current rock mechanic model that tie acoustic properties to petrophysical properties.

This study has direct implications for calibrating increasingly popular stochastic inversion techniques. These techniques aim at inversing the seismic signal beyond the resolution of normal acoustic inversion by applying an element of stochastic distribution to the inversion process. Like every stochastic process, it requires not only knowledge of the variance of the properties to inverse for, but also the spatial distribution of the variance. This variance is typically provided by the variograms, which will be a product of the proposed study. This year we will used the variogram from last year to run synthetic seismic and stochastic inversion experiments and sensitivity analyses. Ultimately the proposed research on spatial variation of acoustic properties of carbonate sediment will improve our ability

Rock-Strength Characterization

The RCRL group has a growing database of rock-strength measurements in carbonates, now requiring a formalized database to capture essential elements about rock properties, facies, pore types, and unconfined compressive strength measurements (UCS). Over the past 2 years, we have developed a database that highlights variations in rock strength and resultant fracture development when subjected to deformation. We think that this research represents a distinct advance in how fractured reservoir models are developed. Linking facies, lithology, pore type, and rock properties to appropriate fracture-intensity variations will be a differential factor in characterizing carbonate reservoirs.

SUMMARY

RCRL is an integrated carbonate research group whose major 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 to better understand and describe the 3D reservoir environment. 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 to develop the "best practice" approach to integrated reservoir characterization.

In 2011 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@mail.utexas.edu) or Bob Loucks (512-471-0366 or bob.loucks@beg.utexas.edu).

APPENDIX A: RECENT AND ACTIVE RCRL STUDENTS

Graduated

Beatriz Garcia-Fresca, Ph.D., Supervisors—J. Lucia and J. Sharp Jr.; Committee—C. Kerans, G. Jones, J. Banner

Title of thesis—Outcrop-Constrained Flow and Transport Models of Reflux Dolomitization

Research objectives— (1) Extend the sequence stratigraphic model of the San Andres Formation on the Algerita Escarpment, Guadalupe Mountains, New Mexico. (2) Construct a petrophysical model of the San Andres outcrop constrained by sequence stratigraphy to show the distribution of porosity and permeability at the time of deposition. (3) Conduct density-flow experiments assuming that hypersaline water occurs at every exposure event, as dictated by the sequence stratigraphic model. (4) Compare resulting dolostone patterns with existing dolostone distribution to test the hypothesis that the dolostone is a product of hypersaline reflux. (5) Using a single-cycle Cretaceous outcrop near Austin, Texas, build transport models to test the impact of dolomitization rate on the development of multiple beds of dolostone.

Jerry Bellian, Ph. D., Supervisor—C. Kerans; Committee —J. Lucia, R. Loucks, J. Banner, R. Steel

Title of thesis— Laser-Mapping and 3D Reconstruction of the Lower Ordovician El Paso Group Breccia Collapse Breccias, Franklin Mountains

Research Objectives— (1) Develop an integrated 3D model of Franklin Mt. collapse breccia complexes using airborne lidar, surface facies and stratigraphic mapping, and structural mapping and (2) develop new workflows for use of airborne lidar volumes in geologic interpretation.

Randy Caber, M.Sc., Co-supervisors—R. Loucks and X. Janson; Committee—C. Kerans and J. Banner

Title of thesis—Paleocave and Associated Features in the Lower Cretaceous Segovia Formation, Western Edwards Plateau—West Texas

Research objectives: (1) Understand the origin and timing of an extensive cave system in the Segovia Formation, (2) define the morphology of the voids and relate to past local and regional hydrology and geology, and (3) characterize cave fill as to source and depositional processes.

Joseph El Azzi, M.Sc., Supervisor—C. Kerans; Committee—X. Janson and R. Steel

Title of thesis—Stratigraphy and 3D Model of an Icehouse Slope System, Early Permian, Southern Outlier, Hueco Mountains

Research objectives—(1) Conduct a detailed 3D digital mapping project in the Early Permian Hueco Group carbonates of the Southern Outlier of the Hueco Mountains, which is largely a shelf margin-to-basin profile, and (2) develop a 3D model of slope architectural elements for icehouse carbonate slopes.

Active

Ryan Phelps, Ph.D. candidate, Supervisor—C. Kerans; Committee—R. Loucks, W. Fisher, R. Steel, R. Scott, X. Janson, and S. Gulick

Title of thesis—The Albian Carbonate Platform of Texas: Shelf Margin Architecture, Cyclicity, and Carbon Isotope Stratigraphy

Research objectives—(1) Revise and modernize well-known shelf stratigraphy of the Glen Rose-Edwards system of the outcrop belt and integrate with subsurface log and core data, with an emphasis on sequence framework and autocyclicity; (2) use recently acquired core, log, and seismic data to document the tectono-stratigraphic evolution of the Albian carbonate platform margin of the Gulf of Mexico in South Texas; and (3) develop a carbon isotope chemostratigraphy for the Albian of Texas.

Selin Erzeybek, Ph.D. candidate, Supervisor—Sanjay Srinivasan; Committee—X. Janson and C. Zahm

Title of thesis—Characterization and Modeling of Karst Reservoir Using Multiple-Point Statistics on a Nongridded Basis

Research objectives—(1) Better characterize spatial distribution of the paleocave/paleokarst features that are represented by fracture networks, central line of the cave, etc., and explore how to extract the statistical properties of these complex structures; (2) simulate the fracture networks and cave/karst patterns by integration of stochastic methods and extracted statistical information; (3) apply the constructed simulation algorithm to field data by conditioning the well information using data from Yates field in West Texas; and (4) analyze the implications of updated paleocave/paleokarst models on fluid flow and production data.

David Hull, M.Sc. candidate, Supervisors—R. Loucks and K. Milliken; Committee—R. Steel and C. Kerans

Title of thesis—Lower Cretaceous Pearsall Shale Gas System in Southwest Texas: a Mixed Carbonate/Terrigenous System

Research objectives—Define a hybrid shale gas system, including regional variation in facies, reservoir quality, and geochemistry.

Rachel Aisner, M.Sc. candidate, Supervisor—C. Kerans; Committee—R. Steel and R. Scott

Title of thesis—Anatomy of Patch Reefs and Platform-Interior Carbonates of the Aptian-Albian Mural Limestone of the Bisbee Area, AZ

Research objectives—Develop stratal architecture and associated lithofacies distribution.

Charles Harman, M.Sc. candidate, Supervisor—C. Kerans; Committee—not selected

Title of thesis—*Pending*: Sequence Analysis of Seven Rivers Formation, Manzanita Ridge and North Ward Estes field

Research objectives—Improve understanding of the interplay between carbonate and siliciclastic facies within a sequence framework on a mixed system shelf.

Mahmood Al-Nazgahah, M.Sc. candidate, Supervisor—C. Kerans, Committee—not yet selected

Title of thesis—undeclared

Research objectives—Undeclared, general area of carbonate reservoir architecture

Nabiel Eldam, M.Sc. candidate, Co-supervisors—C. Kerans and C. Zahm; Committee—not yet selected

Title of research—Structural Controls on Paleokarst Development, Madison Limestone, Devils Canyon Area, Wyoming

Research objectives—(1) Evaluate 3D geometry of paleokarst systems using RTK GPS and ground-based lidar, (2) examine importance of structural control on karst spacing and orientation, (3) establish criteria for distinguishing between evaporite-removal karst systems and epigenetic surface karst systems.

Travis Kloss, M.Sc. candidate, Co-supervisors—C. Kerans and C. Zahm; Committee—not yet selected

Title of thesis—Evolution of a Combined Epigenetic and Evaporite Removal Paleokarst Complex, Mississippian Madison Group, Wyoming

Research objectives—Use information from detailed paleokarst mapping and karst facies analysis to better understand the origin and timing of karst-associated processes within the Madison Limestone.

Eric Anderson, M.Sc. candidate, Supervisor—C. Kerans, C. Zahm; Committee—undeclared

Title of thesis— Not yet selected

Research objectives— A study of the Southern Brokeoff Mountains, NM, using petrophysical analysis, ground-based lidar, and fracture-intensity grids to create regional-scale maps and 3D fault/fracture models within Permian margin facies.

Nathan Jones, M.Sc. candidate, Supervisor —C. Kerans; Committee—undeclared

Title of thesis— Not yet selected

Research objectives—Tentative plan of surface and airborne lidar characterization of syndepositional shelf-margin fracture systems and related collapse events within the Tansill-equivalent reef margin.