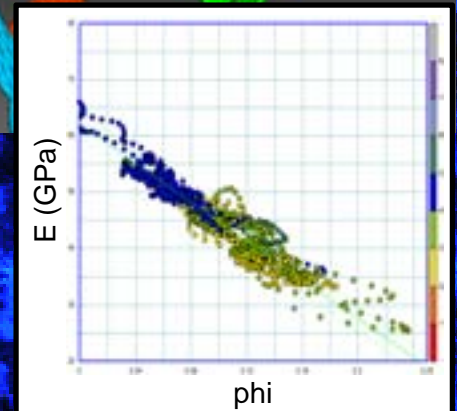
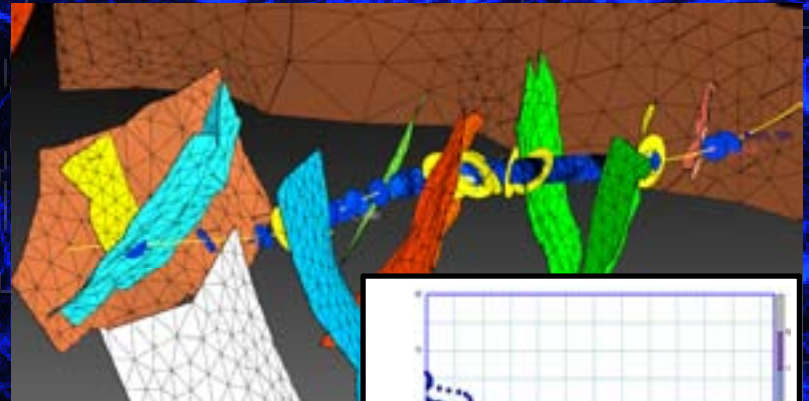
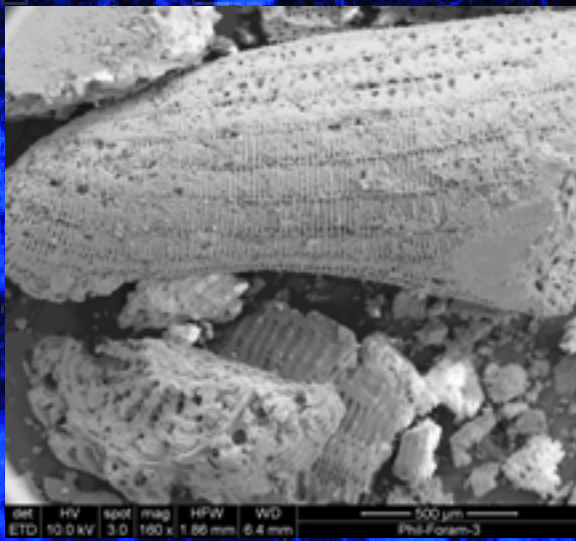




Reservoir Characterization
Research Laboratory
for Carbonate Studies

Executive Summary and Prospectus for 2012

Charles Kerans and Robert Loucks: Co-Principal Investigators



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Reservoir Characterization Research Laboratory for Carbonate Studies

Research Plans for 2012

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

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Cover Photo: Background: Photomicrograph of Tertiary deposits under blue fluorescent light highlighting microporosity. Upper left (B&W): SEM view of a modern large benthic foraminifera. Upper right: 3D view of fault, fault damage zones and associated fractures along with cross plot of Young's modulus versus porosity colored by mechanical facies. Bottom: View of the margin to slope transition in the Sella Platform, The Dolomites, Italy.

Reservoir Characterization Research Laboratory Research Plans for 2012

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Reservoir Characterization Research Laboratory

Research Plans for 2012

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 2012. A list of recent sponsors is presented in Table 1. In 2012 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 (2012 and 2013) 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
 Lidar Research Position (search in progress)

Associate Staff

Dr. Steve Ruppel, Senior Research Scientist, Geologist
 Dr. Hongliu Zeng, Research Scientist, Geophysicist
 Dr. Gregory Frébourg, Research Associate, Geologist
 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.

Aramco	Golder Associates
Anadarko	Husky
Apache	JAPEX
Baker Hughes	KinderMorgan
BG International	Maersk
BGP	OXY
BHP	Petrobras
BP	Pioneer
BPC	Shell
Chevron	Statoil
ConocoPhillips	Suncor
ExxonMobil	Whiting

Table 1. 2010 RCRL Sponsors

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.

RCRL RESEARCH PROGRAM

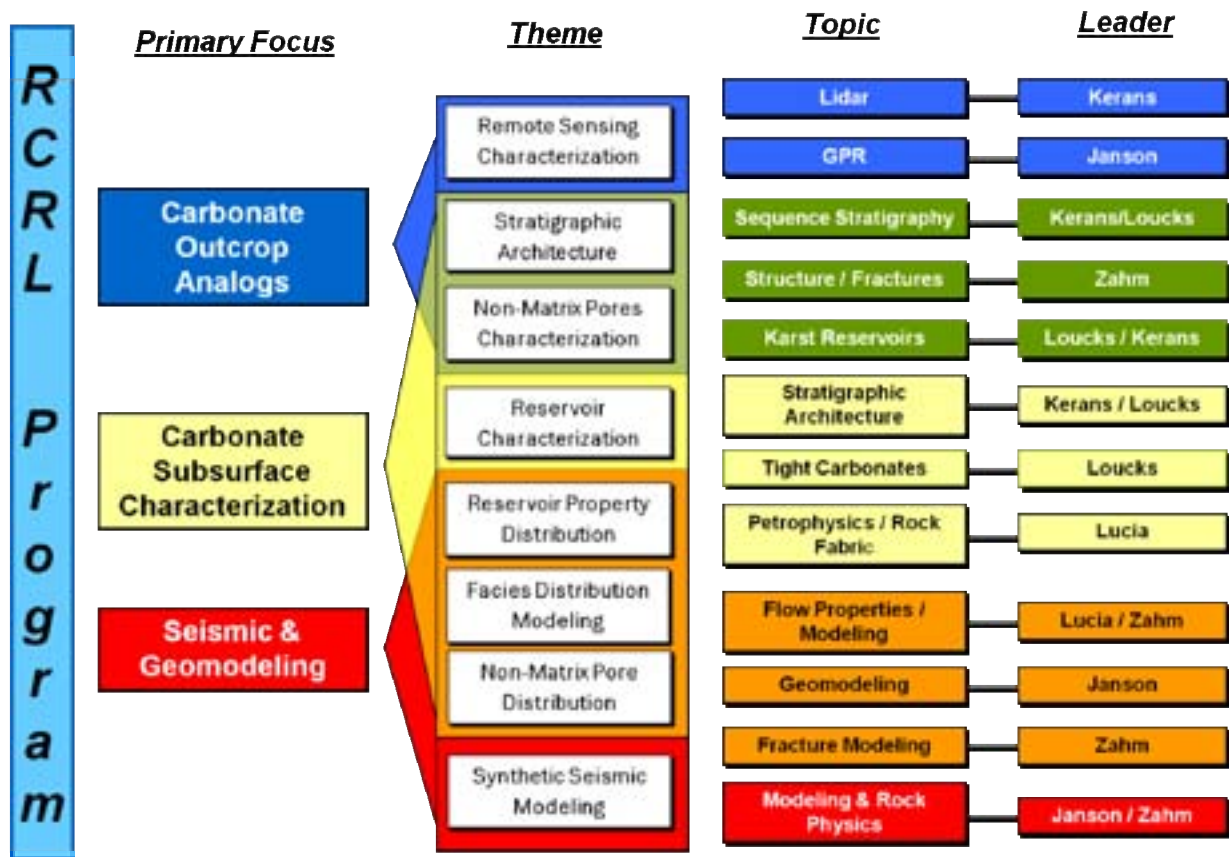


Figure 1. The RCRL Research Program, primary research leaders and integration of overlapping themes.

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 2012. This course will use the unique suite of Paleozoic carbonate outcrops in the classical West Texas/New Mexico region to illustrate both exploration and reservoir-scale stratigraphic architecture. This field trip will visit a suite of outcrops that highlight different platform geometries and cycle architectures within a range of climatic conditions, including the Ordovician greenhouse-dominated system through the transitional to peak icehouse-conditions in Mississippian to Permian outcrops located in the Franklin, Sacramento, Hueco, and Guadalupe Mountains. This course emphasizes detailed stratal geometry variations between the different systems, and has focused discussions on the recognition, prediction, and model strategies of these different architectural elements for application in subsurface reservoirs. Data examined will include outcrops, cores, and subsurface analog data. This course will contain both field lectures and hands-on field exercises such as measuring sections, mapping, cycle variability, and stratal geometries, combined with evening discussions/lectures. This trip is ideal for geologists and engineers with 1-5 years of experience who actively work with subsurface data. The participants will gain substantial insight about the systems they are studying through working on these classic RCRL-researched outcrops. This trip is tentatively planned for the third week of May 2012.

We will also be offering a classroom seminar in 2012. It will be an updated version of the popular reservoir characterization/modeling course that RCRL has previously conducted. New insights from geophysics and fracture prediction will be incorporated into this workshop.

We will send a more detailed program of field trip and workshop early in 2012.

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. In 2011 RCRL researchers visited several companies in China and presented highlight of our research and discussed potential joint research. We also participated in a study of Miocene carbonate in the Kangean Island with JAPEx and as part of the project we hosted a visiting scientist from JAPEx for a year in Austin. We also conducted field reconnaissance in the Glass Mountains with a group of geoscientists from Whiting, Concho, and Exxon-Mobil to ascertain the potential of outcrop analog work targeting the Bone Spring systems. We participated with Shell Research to reconnoiter the classic Triassic carbonates of the Dolomites in Italy. These outcrops can be used as an excellent example of reservoirs on associated with isolated carbonate platforms. A several day short course including a central and south Texas fieldtrip was conducted with Shell. In addition, RCRL researcher visited several companies for one on one interaction and review of our research goals and their applicability to each company's specific assest and issues.

Each of these research interaction 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 2012

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, matrix pores, karst, and fractures. In the 24 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 and mechanical stratigraphy), (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 2012, we are focusing research efforts on five main themes: (1) carbonate shelf-to-basin systems, (2) fault-related fractures within sequence stratigraphic frameworks, (3) evaporite paleokarst systems, (4) Tertiary carbonate systems, and (5) tight carbonate reservoirs (including micropore-dominated reservoirs). In addition, we will continue to add to our foundational work on rock properties characterization including rock strength, velocity variability and acoustic properties.

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

CARBONATE SHELF-TO-BASIN SYSTEMS

Understanding the dynamics of platform to slope transitions including nature 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 for understanding production in fractured steep-rimming microbial systems. Field applications for 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. Three datasets will receive attention this coming year to gain in-depth understanding of steep microbial rim to slope settings; (1) Tansill-age Capitan exposures in the Rattlesnake-Walnut area of the Guadalupe Mountains, (2) the Triassic Sella Platform outcrops of the Dolomite Alps, and (3) Cretaceous Word Field shelf and shelf-margin settings in the subsurface of south Texas.

Airborne Lidar-Assisted Regional Framework of the Guadalupe Mountains

RCRL plans to keep building on the ongoing stratigraphic and structural understanding of the larger Guadalupian shelf-to-basin system in 2012. Using the existing combination of airborne and ground-based lidar in several canyons we will start to address the interaction of stratigraphy and brittle failure/growth faulting of the shelf-crest to slope profile. This steep microbially-rimmed platform is an excellent outcrop analog for steep microbial margins such as Tengiz and Karachaganak and with the initiation of work here by Zahm and student Nathan Jones we will build off earlier work by Rush (Rush and Kerans, 2010) on the collapse process in the Walnut Canyon area.

Major themes for 2012 research in the Guadalupe Mountains are: (1) In preparation for the upcoming SEPM Research Conference on the Guadalupe Mountains system, we will bring our regional synthesis/sequence framework for the Guadalupe Mountains together in a first-phase high-resolution model; and (2) Linkage of shelf-margin and slope systems and the role of early syndepositional fracture systems in platform-margin development. 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 (2002) illustrates the importance of syndepositional fractures in Yates shelf strata in Slaughter Canyon. More recently Rush and Kerans (2010), as part of the RCRL program, documented shelf-margin collapse in the Tansill/Capitan margin at Walnut Canyon, and Frost, Budd, and Kerans (in review) 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. We plan to test this supposition through both field work and digital mapping.

Sella Platform and Shelf-Margin System

The Sella Platform in Italy is an isolated steep-sided platform with a dramatic microbial rim and slope. The Sella is perhaps one of the best outcrop analogs for steep microbial-rimmed isolated platforms such as Tengiz and Kashagan in the pre-Caspian Basin and Golden Lane in the western Gulf of Mexico. The 700-800 m relief and complete 360 degree exposure affords a unique opportunity to document the facies, depositional, and structural architecture of a steep microbial platform. In 2012, we will start the characterization process of the Sella through capture of airborne and ground-based lidar data as well as mapping and section measuring in selected canyons. This work will be carried out in conjunction with Rob Forkner from Shell, Nereo Preto of the University of Pavlova, as well as other companies with a vested interest in this style of reservoir development. One product of interest will be a full-platform geomodel that will serve as input for seismic modeling experiments.

Word Field

The Word Field is an Albian Gulf of Mexico platform- to platform-margin Stuart City reservoir. Stratigraphic and seismic images suggest that there may be a large-scale platform margin collapse controlling the limits of production. A suite of 5 (already available) to 10 cores, limited 2D seismic, plus possible 3D seismic data will be sufficient to develop an initial idealized dip profile for this dataset.

FRACTURES WITHIN A CARBONATE SEQUENCE STRATIGRAPHIC FRAMEWORK

Carbonate sequence stratigraphy provides a framework that enables an improved predictive fracture distribution in outcrop exposures 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.

Tectonic Elements of the Maverick Basin and Georgetown Fracture Systems

Exploration within the Maverick Basin has demonstrated economically successful wells that are exploiting hydrocarbons near mapped faults within Cretaceous strata. Utilizing high-resolution seismic data, limited wireline logs, and outcrop analogs, a fracture-related fault damage zone model is being constructed that will identify key elements for successful wells and incorporate recent work performed on fractured carbonate systems.

Integrated Fractured Carbonates Modeling, Campos Basin, Brazil

Following the completion of the Jabuti project, we will continue to develop innovative ways to incorporate seismic attributes, rock strength, and stratigraphy into advanced reservoir fracture modeling for fractured reservoir modeling. We plan to incorporate fault-damage zone models (e.g., elastic-dislocation models) to improve the handling of small through large-fault offsets. We will use the Jabuti data as calibration of the modeling technique and demonstrate how validation of the model must consider the rock strength variability and vertical mechanical facies associations for the model.

Lewis Canyon and Lower Pecos River Canyon Integrated Fracture Model

Recent RCRL meetings have illustrated the matrix model for Lewis Canyon especially emphasizing the mound-facies relationships in the TST of the Albian 19 sequence. In addition, fault-related fracture variations were demonstrated for a select number of faults within the Lewis study area. We plan to develop a full fracture model for the entire data volume (1.6 x 3.5 km) in order to demonstrate the impact of fractures on flow behavior within the facies model present at Lewis. We intend to test three scenarios: matrix only, fracture only, and dual-permeability scenarios for vertical and horizontal well configurations within this well-defined window.

Niobrara Fault Damage Zone in Outcrop-Exposed Oblique Shear Zones

The effort into variations of fault-related fractures within different carbonate lithofacies will continue in southern Colorado examining fracture intensity variations by rock type within the Cretaceous Niobrara formation (approximately Austin chalk age equivalent). An active quarry has exposed an oblique-extensional fault system similar to faults within the Lower Pecos Canyon. Characterizing the fracture system within the Niobrara exposure offers an opportunity to compare deformation response within a similar structural style, but very different lithofacies. The main characterization work will be in the form of Gigapan-lidar fusion aims to elicit spatial relationships such as damage zone size and rock property variations.

Partitioned Fracture Development Related to Stratigraphic Variability and Evaporite Paleokarst, Sheep Mountain Anticline

Fracture development within the Mississippian Madison at Sheep Mountain Anticline has been shown to be partitioned by the mechanical stratigraphic packages observed in outcrop and documented by Sonnenfeld (1996) and Zahm (2011 RCRL meeting). We will provide a more detailed examination of structural elements that partition fractures at the bed, cycle and third-order sequence scale. We will continue lidar and Gigapan acquisitions along the northern railroad canyon exposure. Sheep Mountain anticline is a world-class exposure due to its ideal reservoir scale. Our ultimate goal is to construct a model that incorporates the matrix, evaporite karst, and fractures within the deformed geometry to better understand the effects of each element on the flow performance within a mechanically-stratified reservoir analog.

EVAPORITE PALEOKARST SYSTEMS

Through our research relative to karstification of both carbonates and evaporites, we 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.

Evaporite Paleokarst Characterization and Associated Fracture Development, Cretaceous Kirschberg, Junction, 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 including the development of open shear fractures and faults. This study has developed the concept that the older fracture system stress patterns control the fracture patterns of the much younger suprastratal fracture development. Alternatively, the evaporite horizon may be acting as a strain partitioning horizon, decoupling the overburden rock and the associated deformation from underlying strata. We will continue to test these hypotheses and compare this to other systems.

Evaporite Paleokarst Characterization and Associated Fracture Development, Mississippian Madison Formation, Bighorn Canyon, Montana

The Mississippian Madison Formation exhibits an impressive spectrum of dissolution and karst collapse associated with both carbonates and evaporites. 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.

Geomodeling and Flow Simulation of Karst-Collapse Systems

Karst-collapse systems have distinct reservoir elements that are extremely heterogeneous with matrix, fractures, and touching and non-touching 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 the distribution of essential reservoir elements including matrix, karst collapse breccias along with dissolution enhanced fractures, fracture fills, and deformation-related discrete fractures. We expect many nonunique geomodel solutions, but we hope to highlight key elements to reservoir-flow behavior, including pore volume distribution along with recovery and sweep efficiency.

TERTIARY CARBONATE SYSTEMS

A series of cores from several Southeast Asia reservoirs are being analyzed for stratigraphic architecture, depositional environments, lithofacies, and pore networks as a way to build a program in Tertiary carbonates. The cores are from isolated platforms and cover depositional settings ranging from platform interior, reef-rim, to deeper-water slope systems of Oligocene to Miocene age. On the basis of a few outcrop observations in Indonesia and in the Mediterranean area, combined with core from the Philippines and elsewhere, we have identified a wide range of facies associations, depositional geometries, and stratigraphic architecture that do not fit the classic Tertiary depositional model. We are in the process of establishing improved depositional models that will cover a wider spectrum of Oligo-Miocene platforms. In particular, we are interested in improving our understanding of: (1) carbonate deposition in oligophotic low- and high-energy environments; (2) carbonate deposition and stratigraphic architecture in an extension-tectonic setting; (3) carbonate deposition and stratigraphic architecture of platforms deposited over highly irregular topography; (4) deep-water carbonates associated with Oligo-Miocene platforms; and (5) pore-networks associated with the different lithofacies and diagenetic pathways.

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 the abundance of micropore development. Also, several field areas are being considered for outcrop analog research.

Lower Miocene Isolated Platforms in the Northwest Palawan Area, Philippines

A study is underway on a series of cores from the Northwest Palawan area. The cores cover several isolated, reef-rimmed platforms. We have described depositional facies ranging from platform interior, reef rim, to slope debris flows. The internal architecture of the facies, as well as the diagenesis and associated pore networks, are being analyzed. We are also investigating the use of both smaller and larger foraminifera on recognizing deposition setting over tens of miles.

Lower Miocene Isolated Platform in the Java Sea, Indonesia

We will be describing a series of cores from an isolated Tertiary carbonate platform in the Java Sea. The goals are similar to those described above for the Northwest Palawan area in the Philippines. The advantage of this dataset is that there are several cores available from a single platform which will allow the characterization of facies and pore network heterogeneity.

TOPICAL SUBSURFACE STUDIES

Seismic Facies Mapping of Albian Carbonates of the Stuart City Margin and Maverick Basin

With the completion of Phelps' PhD work (Phelps, 2011) on the Hauterivian-Coniacian strata of the south Texas Comanche shelf and margin, we now have a detailed framework within which to place our ongoing studies. For the 2012 year we plan to build on the study of the Albian (lower Glen Rose, upper Glen Rose) and Cenomanian (Georgetown) carbonates of the Maverick Basin using a combination of the exceptional 3D seismic data in addition to wireline log and some core data. This work, which will be undertaken in conjunction with Newfield's ongoing effort in the Maverick Basin, will focus on clearly documenting the petrophysical character of the suite of seismic facies identified this year. Several producing trends in the Maverick Basin are closely tied to structural features, and the relationship between this fracture-controlled permeability and the regional structural framework will also form a fundamental predictive element of the research direction.

Origin and Petrophysics of Tight Carbonate Reservoirs with Emphasis on Microporous Limestone Reservoirs

We see gas production from "tight" carbonate reservoirs as a significant *unconventional* resource with an important example being the Lower Cretaceous Stuart City Trend in south Texas. We intend to search for other gas fields that produce from low-permeability limestones 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.

Development of Microporous Reservoirs through the Stabilization of High-Mg Calcite Sediments

We have made significant progress on understanding and documenting the process of the transformation of original high-Mg calcite allochems, such as foraminifera and red algae, to low-Mg calcite and associated micropores. Reservoirs analyzed to present include the Upper Jurassic Cotton Valley Lime, Lower Cretaceous Sligo and Stuart City reef trends, and the lower Miocene carbonate buildup in the Philippines. A major conclusion, we are leaning towards, from these observations is that microrhombic calcite formation may just be the normal stabilization

product of high Mg-calcite. No specific diagenetic pathway or fluid is necessary, only a diagenetic environmental disequilibrium change. Micropores result where there is equilibrium within the grain between dissolution and reprecipitation. Where calcium carbonate is added to the grain, cementation occurs occluding pores. Where calcium carbonate leaves the grain, moldic pores develop. This conclusion addresses the varied and contradicting conclusions suggested for the formation of microrhombic calcite and associated micropores. Along with more worldwide examples of micropore-dominated reservoirs, further research of younger samples (Recent and Pleistocene) of carbonates undergoing diagenesis needs to be conducted. Also, laboratory experiments of modern high Mg-calcite grains need to be pursued to see if we can convert modern high Mg-calcite grains into microrhombic calcite.

Origin and Petrophysics of Microspar and Associated Micropores in Carbonate Mud

Samples from the Miocene- to Pliocene age mud-dominated fabrics encountered in the Clino core from the Bahamas are being analyzed to help understand the process of converting carbonate mud into microspar and the associated changes in pore structure and petrophysical properties. The transformation of carbonate mud, composed of chemically unstable aragonite and high-Mg calcite, commonly produces porous and permeable reservoirs in the ancient as noted by numerous Mid-East reservoirs. Several ideas have been presented on this stabilization process, including burial dissolution and coalescive aggrading neomorphism, but our initial results suggest these concepts are wrong. We are finding that the conversion of carbonate lime mud to a microporous microspar fabric is a simple dissolution and reprecipitation process. We want to apply these developing concepts to ancient mud-dominated micropore reservoirs.

Petrophysics of Microporous Tight-Gas Limestone Reservoirs

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 microporous reservoirs 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.

Carbonate Rock Properties and Geomodel Distribution

On the basis of 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 continuing 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 our understanding of the relationship between rock strength and fracture development.

Spatial Distribution of Seismic Properties in Carbonate Rocks

This research project is investigating vertical and lateral seismic velocity heterogeneity in carbonate rocks. We have developed an extensive set of velocity data in an Albian carbonate 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). In the past year we have demonstrated that acoustic velocity has a similar spatial distribution and variance structure as other petrophysical properties with a large amount of small-scale heterogeneities.

This study has direct implications for calibrating increasingly popular stochastic inversion techniques. These techniques aim at inverting 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. 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. This year we will build a detailed, calibrated 3D (pre-and post stack), synthetic model to experiment with stochastic inversion and identify the key parameter that controls the inversion results. In addition, we will apply this knowledge to a real subsurface dataset if a good analog is available.

Geomodeling of Carbonate Reservoirs

The PhD-based karst MPS modeling project by Selin Erzeybeck will be completed. The new methods and algorithms developed by Selin will be tested on the dataset from the Yates karsted field. In addition, using several detailed outcrop models, we will collaborate with Larry Lake in the UT Petroleum and Geosystem Engineering Department to investigate the effects of geomodeling techniques and amount of conditioning data used on pore volume and flow behavior.

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 3 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 the broader stratigraphic architecture (e.g., vertical mechanical facies associations and comparisons between TST-HST styles) to appropriate fracture-intensity variations will be a differential factor in characterizing carbonate reservoirs.

Rock Mechanics Laboratory

The BEG, through a multi-group effort, is constructing a rock physics and mechanics laboratory. Within the lab, we will have the ability to perform triaxial testing to measure the elastic properties including yield strength, Young's, poisson's ratio, and permeability calculations within tight carbonates and sandstones, as well as acoustic properties, including shear and compressional velocity in conventional carbonates and mudrocks.

This new instrument will allow us to: (1) calibrate our outcrop and core measurement hand-held device for velocity and rock strength; (2) investigate the elastic properties of carbonate under varying confining pressure, pore pressure, and fluid type; and (3) investigate the effect of in-situ stress on permeability for various carbonate textures and pore types.

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 to better understand and describe the 3D carbonate reservoir system. We have a multi-faceted 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 2012, 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

Active

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 Non-gridded 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.

Nabiel Eldam, M.Sc. candidate, Co-supervisors—C. Kerans and C. Zahm; Committee—Kerans, Zahm and R. Steel

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.

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

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.

Sam Hiebert, M.Sc. candidate, Supervisor —C. Kerans; Committee—undeclared

Title of thesis— High-Resolution Sequence and Chemstratigraphic Correlations of the Grayburg Formation – Shattuck Escarpment and Plowman Ridge – Testing Models of Shelf-to-Basin Frameworks

Stephanie Woods, R. Loucks and S. Ruppel; Committee—undeclared

Title of thesis— Sequence Stratigraphy, Stratal Architecture, and Lithofacies of the Pennsylvanian Marble Falls Formation in the in central Texas

Research objectives—Through the analysis of a number of complete cored sections, the stratal architecture of the Marble Falls Formation from shelf to basin will be developed. The variety of carbonate and siliciclastic lithofacies will be described and their origin will be investigated.

Travis Kloss, M.Sc. candidate, Co-supervisors—C. Kerans and C. Zahm; Committee—Kerans, Zahm and Fisher

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.

Alex Parker, M.Sc. candidate, Co-supervisors—C. Kerans and C. Zahm; Committee—undeclared

Title of thesis— Not yet selected

Gregory Hurd, PhD. candidate, Supervisor—C. Kerans and X. Janson

Title of thesis— Not yet selected

Research objectives— Carbonate slope rock physics (compactions) and its effect on platform stratigraphic architecture

Graduated

Ryan Phelps, Ph.D. conferred, 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.

David Hull, M.Sc. conferred, 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. conferred, 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. conferred, Supervisor—C. Kerans; Committee—N. Frost and D. Mohrig

Title of thesis—Quantified Facies Distribution and Sequence Geometry of the Yates Formation, Slaughter Canyon, New Mexico

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. conferred, Supervisor—C. Kerans, Committee—W. Fisher, L.T. Smith

Title of thesis—The Sedimentology and Stratigraphy of the Arab D Reservoir, Qatif Field

Research objectives— Sequence and facies analysis of the Arab D reservoir at Qatif

APPENDIX B: RECENT RCRL PUBLICATIONS

- Bergman, K. L., Whestphal, H., Janson, X., Poiriez, A., and Eberli, G. P., 2010, Chapter 2. Controlling parameters on facies geometries of the Bahamas, an isolated carbonate platform environment, *in* Whestphal, H., Eberli, G. P., and Reigl, B., eds., Factors controlling modern carbonate deposition: Springer-Verlag, ISBN:978-90-481-9363-9, p. 5–80.
- Chiaromonte, L., Zoback, M., Friedmann, J., Stamp, V., Zahm, C., 2010, Fracture characterization and fluid flow simulation with geomechanical constraints for a CO₂–EOR and sequestration project Teapot Dome Oil Field, Wyoming, USA, *Energy Procedia*, Volume: 4, Elsevier, Pages: 3973-3980.
- Frost, E.L., III and Kerans, C., 2009, Platform-Margin Trajectory as a Control on Syndepositional Fracture Patterns, Canning Basin, Western Australia, *Journal of Sedimentary Research* February 2009 v. 79 no. 2 p. 44-55
- Frost, E. L., and Kerans, Charles, 2010, Controls on syndepositional fracture patterns, Devonian reef complexes, Canning Basin, Western Australia, *in* Agosta, F., and Tondi, E., eds., *Faulting and fracturing in carbonate rocks: new insights on deformation mechanisms and petrophysical properties: Journal of Structural Geology*, v. 32, p. 1231–1249.
- Hull, D., and Loucks, R. G., 2010, Depositional systems and stratal architecture of the Lower Cretaceous (Aptian) Pearsall Formation in South Texas: *Gulf Coast Association of Geological Societies Transactions*, v. 60, p. 901–906.
- 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.
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- Janson, X., Van Buchem, F., Dromart, G., Eichenseer, H. T., Boichard, R., Dellamonica, X., Bonnaffe, F., and Eberli, G., 2010, Architecture and facies differentiation within a middle Miocene platform, Ermenek, Mut Basin, southern Turkey, *in* Van Buchem, F. S. P.,

- Gerdes, K., and Esteban, M., eds., *Mesozoic and Cenozoic carbonate systems of the Mediterranean and the Middle East: stratigraphic and diagenetic reference models*: Geological Society, London, Special Publications, 329, p. 265–290.
- Kurtzman, D., El Azzi, J. A., Lucia, F. J., Bellian, J. A., Zahm, C., and Janson, X., 2009, Improving fractured carbonate-reservoir characterization with remote sensing of beds, fractures, and vugs: *Geosphere*, v. 5, no. 2, p. 126–139.
- Loucks, R. G., 2010, Intrastratal and suprastratal deformation associated with collapsed-paleocave systems, 44th U.S. Rock Mechanics Symposium and 5th U.S.–Canada Rock Mechanics Symposium Proceedings, Salt Lake City, June 27–30: ARMA 10-141, 7 p.
- Loucks, R. G., Kerans, C., Janson, X., and Marx Romano, M. A., 2011, Lithofacies analysis and stratigraphic architecture of a deep-water carbonate debris apron: Lower Cretaceous (latest Aptian to latest Albian) Tamabra Formation, Poza Rica field area, Mexico: SEPM (Society for Sedimentary Geology), Special Publication No. 96, p. 367–389.
- McNeill, D. F., Janson, X., Bergman, K. L., and Eberli, G., 2010, Chapter 3. Belize: a modern example of a mixed carbonate-siliciclastic shelf, in Whestphal, H., Eberli, G. P., and Reigl, B., eds., *Factors controlling modern carbonate deposition*: Springer-Verlag, ISBN: 978-90-481-9363-9, p. 81–144.
- Owens, L., and C. Kerans, 2010, Revisiting the Cow Creek Limestone: Facies architecture and depositional history of a greenhouse strandplain: *Gulf Coast Association of Geological Societies Transactions*, v. 60, p. 907-915.
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- Playton, T. E., Janson, X., and Kerans, C., 2011, Chapter 18. Carbonate slopes, in James, N. P., and Dalrymple, R. W., eds., *Facies models 4: St. Johns, Newfoundland*, Geological Association of Canada, p. 449–476.
- Riegl, B., Poiriez, A., Janson, X., and Bergman, K. L., 2010, Chapter 4. The Gulf: facies belts, physical, chemical, and biological parameters of sedimentation on a carbonate ramp, in Whestphal, H., Eberli, G. P., and Reigl, B., eds., *Factors controlling modern carbonate deposition*: Springer-Verlag, ISBN: 978-90-481-9363-9, p. 145–215.
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- Zeng, H., Wang, G. Z., Loucks, R. G., Janson, X., Xia, Y. P., and Xu, L. G., 2011, Seismic geomorphologic, core, and outcrop expression of an Ordovician paleokarst system in north-central Tarim Basin, China, *in* 30th Annual GCSSEPM Foundation Bob F. Perkins Research Conference, December 5-8, 2010, Houston, Texas, p. 73-87.