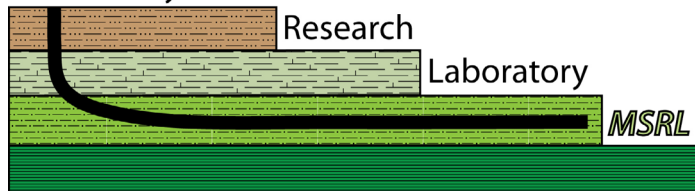


MUDROCK SYSTEM RESEARCH LABORATORY

2015 PROSPECTUS

Mudrock Systems



BUREAU OF
ECONOMIC
GEOLOGY

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Research Plans for 20154

Executive summary 4

Funding 4

MSRL Program4

MSRL sponsors4

Areas of interest4

Information transfer and database 5

Contact information 5

Who we are6

Sedimentology and Stratigraphy7

Dr. Stephen C. Ruppel8

Dr. Gregory Frébourg 10

Dr. Seay Nance 12

Dr. Scott Hamlin 13

Robert Baumgardner, M.A. 14

Geochemistry 15

Dr. Harry Rowe 16

Dr. Tongwei Zhang17

Dr. Xun Sun.....18

Petrography and pore network 19

Dr. Robert G. Loucks 20

Dr. Kitty Milliken21

Dr. Jiemin Lu22

Dr. Robert M. Reed23

Engineering and Modeling25

Dr. Farzam Javadpour 26

Dr. Sheng Peng27

Dr. Hugh Daigle28

Dr. Ray Eastwood30

Data Distribution 31

Cari Breton B.A.32

Students and Teaching 33

Lucy Ko 34

MSRL Students35

Geology of Mudrock Systems class 36

Laboratories, Facilities and Equipment37

MUDROCK SYSTEM RESEARCH LABORATORY

BUREAU OF ECONOMIC GEOLOGY, JACKSON SCHOOL OF GEOSCIENCES, UNIVERSITY OF TEXAS AT AUSTIN

Research Plans for 2015

Executive summary

The Mudrock System Research Laboratory (MSRL) is an industrial research consortium in the Jackson School of Geosciences at the University of Texas at Austin, focused on the study of hydrocarbon bearing unconventional resources in fine grained sedimentary formations and systems. It is run by the Bureau of Economic Geology (University of Texas at Austin). The mission of MSRL is to use integrated multidisciplinary datasets (outcrop and subsurface geology, geochemistry, geophysics and petrophysics) to understand depositional dynamics, environments and conditions of mudrock systems, and provide scientific tools to help increase exploration and exploitation efficiency.

Funding

We invite you to join or participate in the continuation of the MSRL industry research consortium for 2015. A list of recent sponsors is presented below. In 2015, the annual MSRL Industrial Associates contribution to the program will continue to be \$50,000 per year. The annual meeting is usually held early spring each year and reserved for sponsors from the previous year.

MSRL Program

The MSRL program started in 2009 and has run continuously since, receiving support from a growing number of sponsors.

MSRL sponsors:

ANADARKO, APACHE, BP, BHP BILLITON, CENTRICA, CENOVUS, CHESAPEAKE, CIMA, CIMAREX, CHEVRON, CONCHO, CONOCOPHILIPS, CYPRESS, DEVON, ENCANA, ENI, EOG, EXCO, EXXONMOBIL, HESS, HUSKY, KEROGEN, IMP, MARATHON, MURPHY, NEWFIELD, OXY, PENN WEST, PENN VIRGINIA, PIONEER, QEP, SAMSON, SHELL, STATOIL, TALISMAN, TEXAS AMERICAN RESOURCES, THE UNCONVENTIONALS, US ENERCORP, VALENCE, YPF.

Sponsors are currently interested in a range of domestic and international unconventional mudrock reservoirs from the Paleozoic to Mesozoic, deposited in deep water marine to lacustrine environments. Sponsor

funding is supplemented by other grants, which supports between 17 professional staff members and 19 graduate student research assistants, as well as excellent computer, editing, and graphics services.

Staff members have had extensive industry experience or have worked closely with industry, and they are well aware of the challenges and questions facing development geoscientists and engineers. We are also proud of our graduate students associated with MSRL.

Areas of interest

The primary focus of the MSRL research program is the characterization of mudrock systems. To this effect, we use a multidisciplinary approach, combining understanding of the small to large scale of depositional dynamics and controls of sediment fluxes, study of core to basin scale stratal architecture of unconventional subsurface formations, paleoenvironmental geochemical proxies and petrological studies from organic and mineral geochemistry down to the nanopore network characterization. Our research-focus areas, themes, and topics have been developed out of our experience and feedback from our sponsorship, and we strive to be the foremost research group in integrated mudrock characterization.

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 unconventional challenges.

Information transfer and database

Our industrial sponsors receive research results at annual review meetings (held in the Spring), in short courses, during mentoring activities, in publications, DVD's or other physical digital storage medias, and, implemented this year, our members-only MSRL website database.

MSRL WEBSITE

This online searchable database allows us to provide exclusive access to collective research and makes previously presented material easy to locate and download from anywhere in the world. Logon and password are renewed each year of sponsorship. This database includes previous, annotated presentations, maps, core photos, petrophysical data, core descriptions, field guides and any other released data. As of mid-March, its volume reached over 41Gb, and is growing.

These data are organized primarily by formation, then by well and data type. Data are also cross-referenced and searchable by data type. The structure and content of the database are described in an Excel workbook file. This

file also contains a master well list showing basic header information and available data types per well. A basic approach to the data directory and website organization allows maximum control to the end user and ensures flexibility moving forward. Feedback from MSRL members regarding use of the website and treatment of the data is strongly encouraged.

Along with rock-based data, the website hosts a constantly expanding catalogue of research and educational resources available for download: 54 publications, 19 theses or dissertations, 60 MSRL meeting posters, 22 posters or presentation from outside research meetings and 119 slideshows with video recordings of presentations given at past MSRL meetings.

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2013 MSRL meeting fieldtrip on the Eagle Ford/Boquillas and other Cretaceous strata along HWY 90 roadcuts in Val Verde Co.

WHO WE ARE:

RESEARCH STAFF:

Dr. Stephen C. Ruppel
Senior Research Scientist, Principal investigator

Dr. Robert Loucks
Senior Research Scientist, Reservoir quality specialist

Dr. Kitty Milliken
Senior Research Scientist, Petrographer

Dr. Harry Rowe
Research Scientist, Geochemist/paleoceanographer

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Research Scientist, Flow engineer and modeler

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Dr. Robert M. Reed
Research Scientist Associate, Structural Geologist/micro- and nanostructures specialist

Robert Baumgardner, M.A.
Research Scientist Associate, Geologist

Dr. Ray Eastwood
Consultant, Petrophysicist

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Postdoctoral Fellow, Chemist/organic geochemist

SUPPORT STAFF:

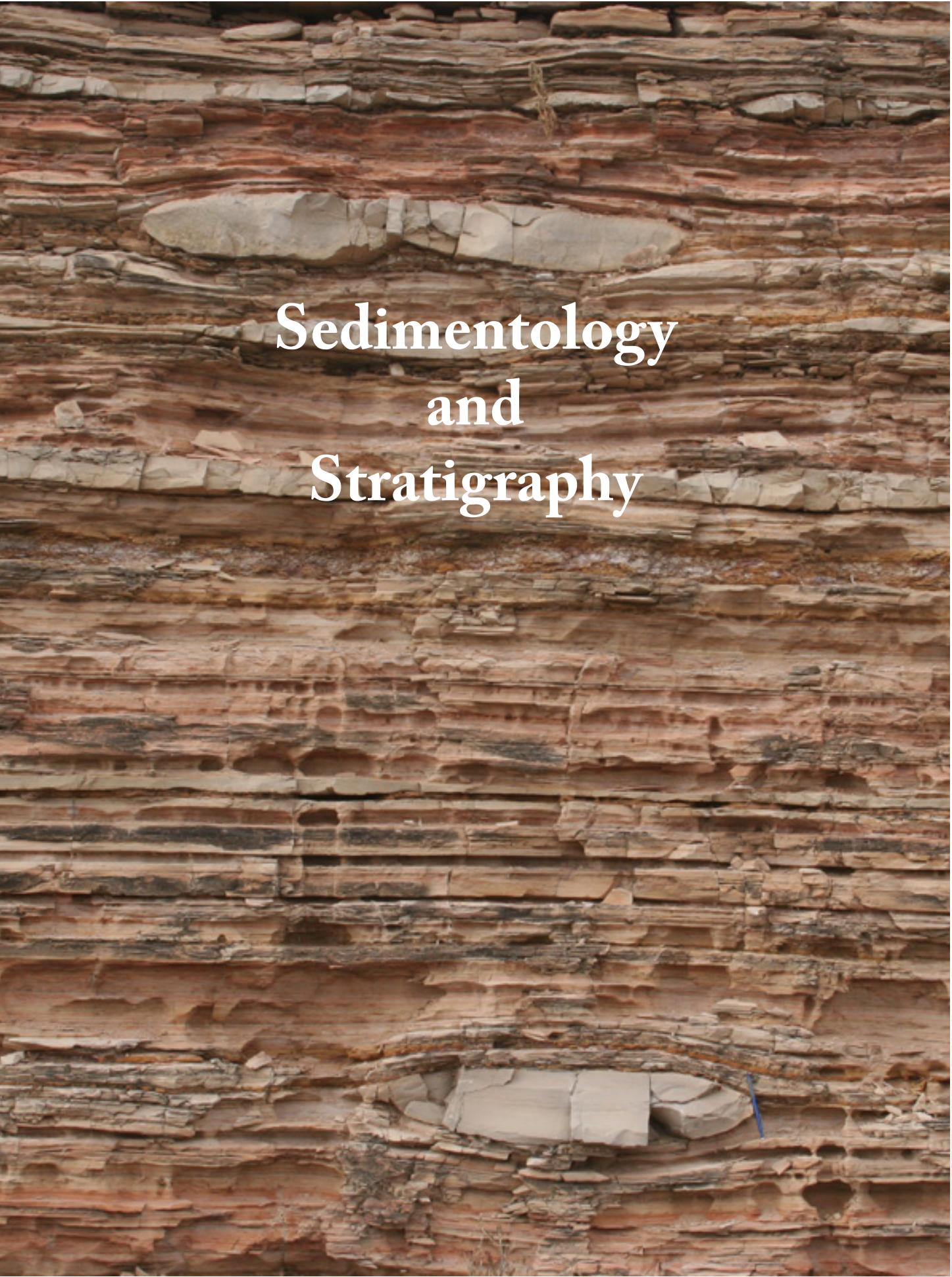
Cari Breton, B.A.
Research scientist Associate, GIS and database specialist

J. Evan Sivil, B.A.
Research Scientist Associate, Geochemistry laboratory superintendent

Zain Abdi MSc.
Research Scientist Associate, Geochemistry laboratory technician

Krystal Heibel, BSc.
Research Scientist Associate, Geochemistry laboratory technician (graduate student Fall 2015)

STUDENTS (with degree sought):
Ahmed Alnabawi (Ph.D.), Jesse Berney (MS), Daniel Enriquez (MS), Kathryn Fry (MS), Kyle Gabb (MS), Hector Garza, (BSc, intern) Ningjie Hu (MS), Lucy Ko (Ph.D.), Justin Mauck (MS), Rita Bitar Nebme (MS), Michael Ni-eto (MS), Lauren Redmond (MS), Reed Roush (MS), James “Jake” Schulz (MS).





Dr. Stephen C. Ruppel
Senior Research Scientist
Principal Investigator

FOCUS: FACIES, ARCHITECTURE, SEDIMENT FLUX, BED CONTINUITY, SEQUENCE STRATIGRAPHY, DIAGENESIS

My research is focused on one primary goal: defining facies architecture and continuity in mudrock systems. To reach this goal I am employing a range of tools and observations at a variety of scales. Integrated X-ray fluorescence (XRF) chemostratigraphy is perhaps the most fundamental part of this research. I am using XRF major element data collected by MSRL geochemist Harry Rowe and others to develop a basis for defining the vertical stacking patterns of mineralogical facies. By integrating X-ray diffraction (XRD) data with XRF data it is possible to produce a reliable and reproducible record of the high frequency changes in mineralogy that can be related to other rock properties (e.g., rock strength, pore types, hydrocarbon saturation, etc) and borehole logs. When combined with microscopy studies, these major element data can be used to define variations in sediment type, sediment supply, and depositional environment. An important goal of this work is to establish interpretation rules for applying XRF element data to facies characterization and to define how such rules vary in mudrock systems both within and between basins and formations.

XRF trace element data are being integrated with major element data to define changes in bottom water redox conditions which relate to organic matter production and preservation and thus to TOC distribution. These data also provide a basis for calibrating borehole gamma ray response to TOC abundance.

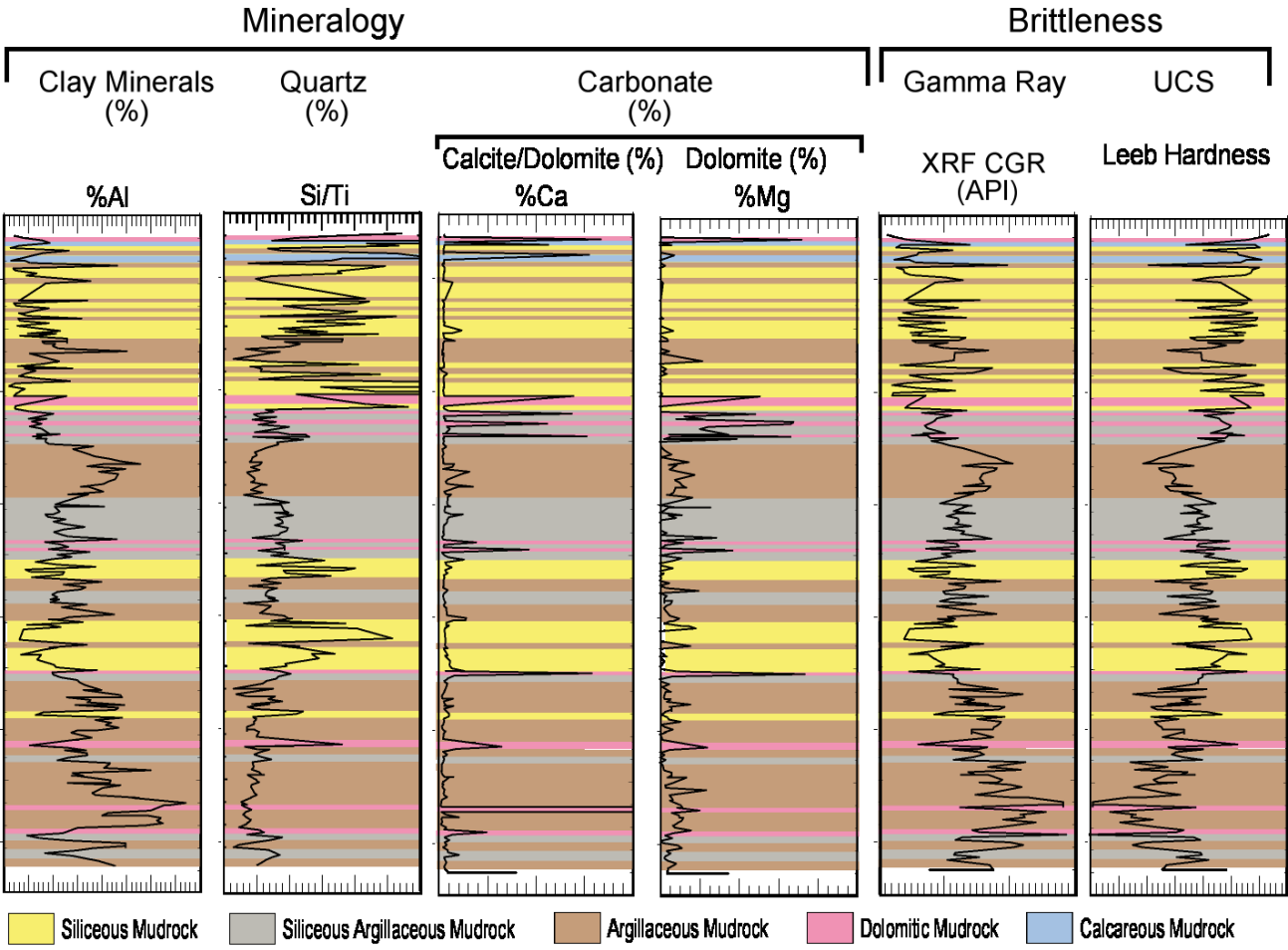
The ultimate goal of the chemostratigraphic research described above is to develop depositional models that can be used to define and predict trends in facies and basic rock attributes, both vertical and horizontal, across a basin. To do this I am examining how 1D vertical facies trends defined in cores vary laterally by directly comparing available core XRF data sets. In the Eagle Ford Group, we constrain these comparisons by integrating chemostratigraphic data with well logs and where possible with biostratigraphic data, stable isotope data, and U-Pb dating. However, even with these temporal controls, true facies continuity and correlatability cannot in most cases be determined from 1D data except perhaps at large scales.

To gain more insight into true continuity I am working with MSRL sedimentologist Greg Frebourg to document facies continuity in outcrop sections. Preliminary results of these studies suggest highly limited continuity of both carbonate rich facies and ash beds, the two most readily identifiable Eagle Ford Group core facies. We hope to examine lateral continuity in the Eagle Ford mark facies using horizontal cores. This work also involves developing an understanding of bottom current transport and the associated bedforms and their geometries. Early results of these studies suggest that most facies

Another factor that must be examined in defining facies continuity is diagenesis. All studied mudrock systems display variable amounts of diagenesis, perhaps the most important of which involves the formation of calcitic or dolomitic cements (e.g., in the Woodford, Barnett, Haynesville, Eagle Ford, etc). Because these diagenetic phases can be closely associated with depositional bedforms developing process-response models in some mudrock systems is even more complicated. To assess the role of diagenesis in these systems I am gathering sediment and cement particle distribution data and collecting stable isotope analyses of carbonate end-member phases to better define the processes and setting of diagenetic crystal growth.

Lastly, because sediment body geometries are a function of sediment supply and source I am collaborating with Frebourg, Rowe, and MSRL Sedimentologist Robert Loucks to better understand and define detrital versus biogenic sediment sources and types. Understanding the controls of open ocean biogenic sediment productivity is

particularly important as biogenic sediment dominates many mudrock systems. To attack this question we are investigating the role of nutrient supply and its causes in the Eagle Ford, a biogenic carbonate system, and the Woodford, a biogenic silica dominated system. Because platform shedding is not the dominant source of sediment in these and many other mudrocks, the applicability of sequence stratigraphic concepts in these systems is questionable. Although cycles are common, their formation is not directly related to changes in accommodation (e.g., relative sea level) but instead is a function of variations in nutrient supply which in turn can be driven by such controls as bottom water overturning, upwelling, volcanism, or climate change in solo or in combination.



Interpreting lithofacies stacking patterns with chemostratigraphy.

Dr. Gregory Frébourg
Research Associate, sedimentologist/micropaleontologist



Dr. Frébourg studying a remote Boquillas Formation (outcropping analogue to the Eagle Ford Formation west of the Pecos River) outcrop in Big Bend National Park, Brewster Co. West Texas.

FOCUS: FUNDAMENTAL AND APPLIED SEDIMENTOLOGY, DEPOSITIONAL ENVIRONMENTS, SEDIMENTARY DYNAMICS, BIOSTRATIGRAPHY AND PALEOENVIRONMENTS.

Outcrop study of interwell scale geometries and variability of the Eagle Ford Fm. in Big Bend National Park, West Texas, USA.

Better understanding of rock attribute continuity results in better data for constructing flow models and defining better well drilling and completion strategies. Most of our knowledge of the producing Eagle Ford Formation comes from subsurface cores and logs. However the one-dimensional nature of these data and their wide spacing preclude accurate determination of interwell variability and continuity. Outcrops provide the opportunity to investigate the lateral variability of sedimentary systems, and mudrocks are no exceptions. However, the mudrock lithology often weathers easily, resulting in poor quality outcrops, unless located within areas of dry climates. The Ernst member of the Boquillas Fm., which crops out over extensive areas of Big Bend National Park, is the equivalent of the most productive

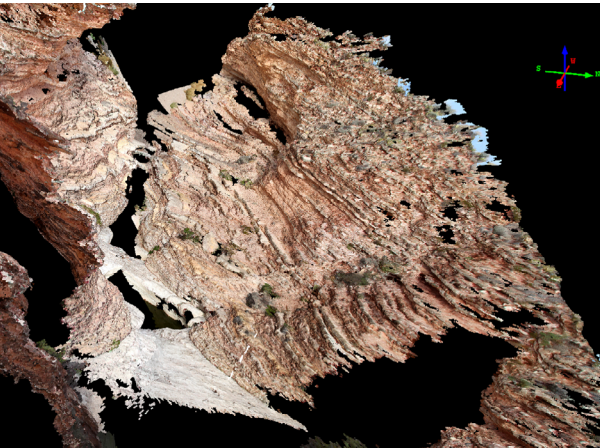
facies of the Eagle Ford in the subsurface. The aim of this project is to gather a detailed knowledge of the depositional facies of the Ernst Member and their variability and upscale these findings to the interwell scale using LIDAR Digital Elevation Models, GigaPans panoramas and photogrammetry.

In the coming months, an exploratory mission will also be led to Big Bend Ranch State park (west of Big Bend National Park) to assess the potential of its Boquillas Fm. outcrops. In this location, the Boquillas Fm. reaches 300 meters (1000') thick and is exposed over extensive areas. If these outcrops are deemed suitable, similar investigations than the ones planned for Big Bend National Park are to be undertaken in Big Bend State Park.

Outcrop study of the Middle Boquillas Fm. (Eagle Ford Fm. analogue) along Highway 90, Val Verde County, West Texas, USA.

The middle member of the Boquillas Fm. is the outcrop analogue of the most productive facies of the Eagle Ford Fm. It crops out in numerous exposures along HWY 90 in Val Verde County. These allow easy observation and study of the sedimentary body geometries and stratigraphy over several tens of meters to up to four hundred meters laterally and up to 20 meters vertically.

Recent missions yielded detailed sedimentological and stratigraphical analyses, which were supplemented by the acquisition of a LIDAR surface model and several GigaPans (high resolution photomosaics). Of those data was derived a model of the controls on lithology, and interpretations of the depositional environment and depositional dynamics.



Tilted view of the 3D cloud point of the Ernst Tinaja outcrop in Big Bend National Park obtained through photogrammetry. 1 voxel = 1 cm, cliff is 45' high

Work on these outcrops will continue, with attempts to integrate mineralogical and elemental analyses within the sedimentary framework. Also, since planktonic foraminifera were found within radiometrically dated ash beds, characterization and/or identification of those species will be undertaken, in the hope of finding useful, easily identifiable marker fossils.

Permian mudrock systems of the Anadarko Basin

The Anadarko Basin is the location of many conventional petroleum systems that were locally sourced. During the Permian starting mid-Permian, the southern margin of the Anadarko Basin was receiving immense volumes of coarse grained sediment derived from the Amarillo Uplift, accumulating in the time transgressive Granite Wash. In contrast, the northern margin of the basin did not receive much sediment. Primary productivity was high and oxygen levels were low on its gentle slope and resulted in the accumulation of organic-matter rich mudrocks. Although those accumulations generated hydrocarbon, their potential as unconventional resources remains high (such as TOC values reaching up to 15% for the 13 Fingers Fm.).

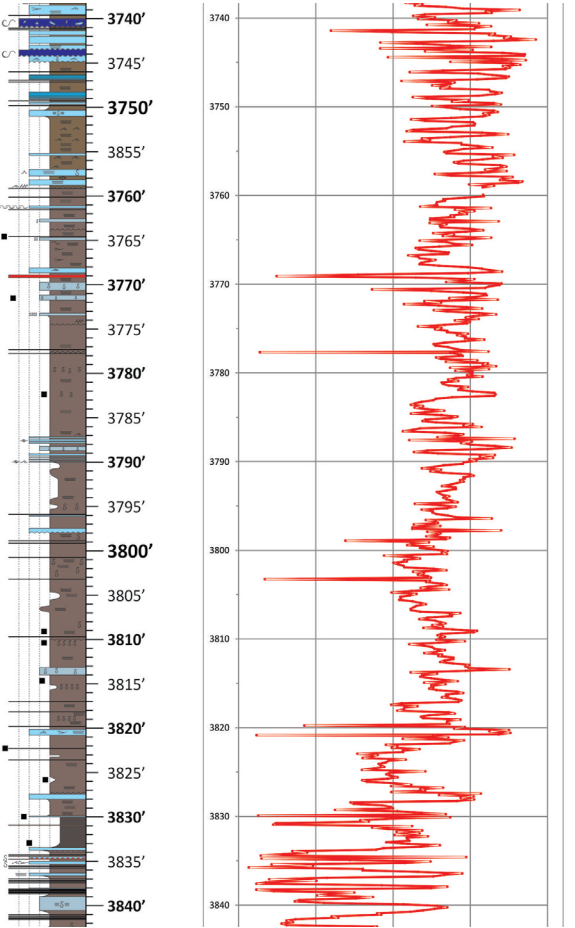
The potential for unconventional exploitation of contemporaneous neighboring basins has been proven, and the Anadarko Basin has been receiving growing attention for the same matter. However, based on accounts from some companies, hydrocarbon production through unconventional methods turned out to be challenging in those rocks.

This project aims to investigate the Permian mudrocks of the northern margin of the Anadarko Basin (13 Fingers Fm., Novi Lime, Marmaton) in order to determine their potential as unconventional resources. Initial in-depth core description, closely spaced XRF data collection and detailed paleo-environmental studies will be followed by organic geochemistry analyses and geo-mechanical investigations to assess and understand the potential of these formations as unconventional targets. Any core and/or data contributions will be welcomed for this project.

Sedimentary dynamics, sediment fluxes and geochemistry

Modern, non-destructive methods of geochemical investigation such as the handheld X-Ray Fluorescence (developed by MSRL geochemist Dr. Harry Rowe) provide geologists with precious, precise and abundant information in little time.

What do these data tell us? Can variations of major and/or trace elements be explained by depositional pro-



Example of an Eagle Ford core description (left - brown facies are mudrocks, blue facies are coarser grained facies) matched with the Calcium weight content curve (right - lateral scale goes from 0 to 40% weight Ca, meaning 0 to 100% calcite). Low Calcium peaks are linked to ash beds (in red).

cesses, dynamics and environments? What are the influence and controls of sediment types and fluxes on other rock properties like brittleness?

Eagle Ford micropaleontology

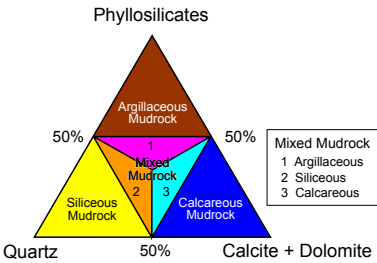
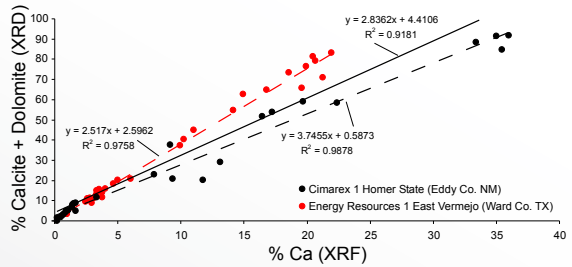
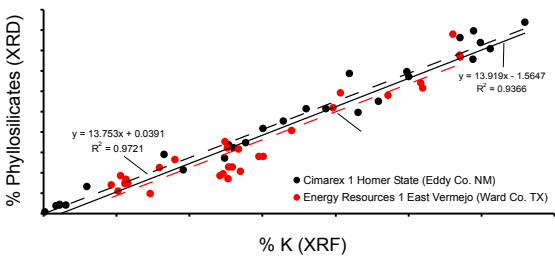
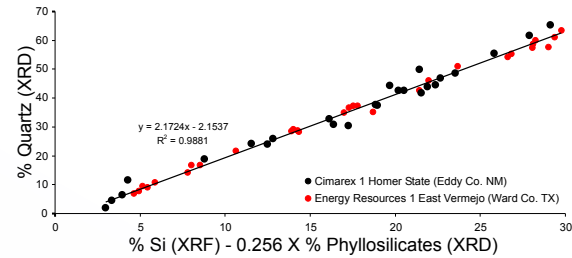
The most productive facies in the Eagle Ford accumulated under hostile sea water conditions. Low levels and/or absence of oxygen were prevalent in most of the water column but the shallow layer. As a consequence, faunal diversity is low, and consists in planktonic, specialized, resilient organisms. Which microfossils one can be used in thin sections for biostratigraphy and/or paleoenvironments?



Dr. Seay Nance
Research Associate, Stratigrapher

FOCUS: STRATIGRAPHY, CHEMOSTRATIGRAPHY, ISOTOPIC GEOCHEMISTRY, PETROGRAPHY, PALEOENVIRONMENTS

Using available Upper Wolfcamp Series cores I intend to investigate relationships between several redox-sensitive elements, nitrogen and carbon isotopes, and organic carbon abundance to determine the best tools to use for interpreting sources of organic material and paleo-environmental conditions present during sedimentation and burial. Petrography will be coordinated with the mineral stratigraphic framework (developed with XRD and XRF data) to interpret the modes of occurrence for quartz (detrital, biogenic) and carbonate (biogenic, cement).



Mineralogy can be estimated from relationships between XRD and XRF data. Facies can be classified according to relative proportions of major minerals and be used to represent mineral stratigraphy. These products can be integrated with other compositional data to interpret lithic cyclicity and depositional environments, and provide guidance for correlation to geophysical well logs.



Dr. Scott Hamlin
Research Associate, Stratigrapher

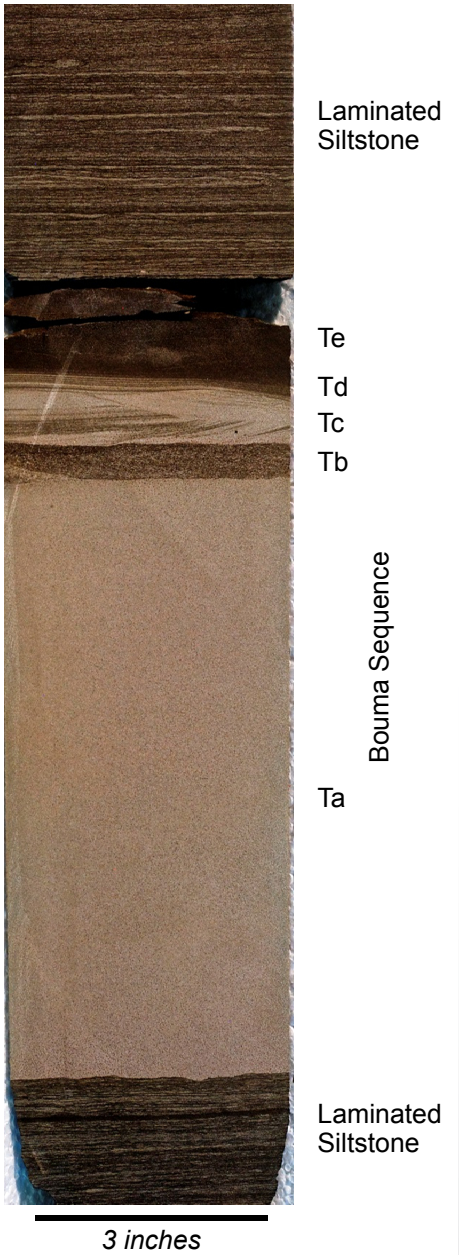
FOCUS: SLOPE AND TOE OF SLOPE DEPOSITIONAL FACIES AND SYSTEMS ALONG THE EASTERN SHELF OF THE MIDLAND BASIN.

Slope and toe of slope depositional facies and systems along the Eastern Shelf of the Midland Basin.

This core- and log-based study covers Pennsylvanian and Lower Permian turbidite and hemipelagic depositional systems in the eastern Midland Basin and the adjacent slope of the Eastern Shelf. A study of the Upper Pennsylvanian Cline Shale by graduate student Reed Roush will be completed in May 2015. Continuing studies will focus on detrital carbonates, turbidite sandstones, and interbedded mudrocks in the Wolfcampian and Leonardian series. Both conventional and unconventional reservoirs will be characterized.

Smithwick Shale lithofacies, stratigraphy, and depositional systems in the southern Fort Worth Basin.

This study covers the Pennsylvanian Smithwick Shale in the south part of the Fort Worth Basin. Although the Smithwick may not be an unconventional prospect (too shallow and immature), it is an excellent shale laboratory, having outcrops, numerous long cores, and wireline logs. This study focuses on stratigraphic relationships between basin-center Smithwick black shale facies and backstepping carbonate platform facies to the west and prograding clastic facies to the east.



Right: Complete Bouma sequence in thin-bedded sandstone, Dean Formation.

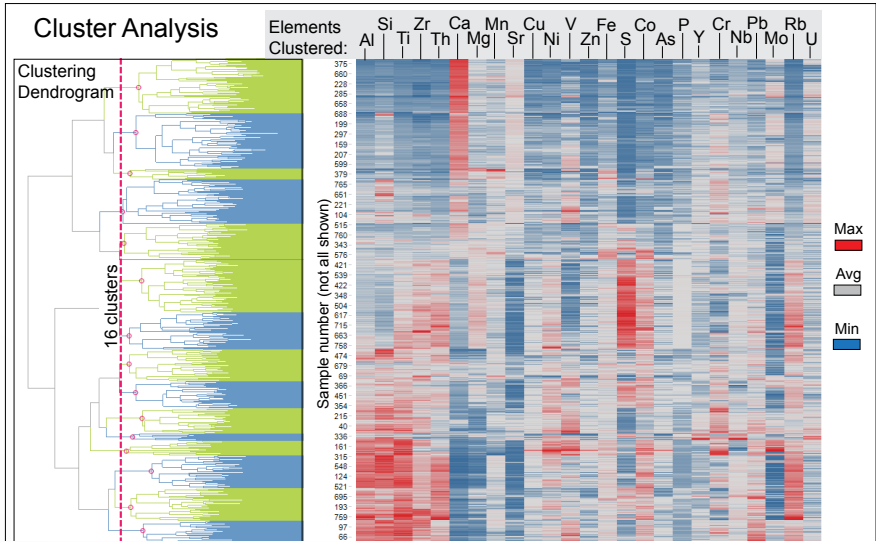


Robert Baumgardner, M.A.
Research Scientist Associate, Geologist

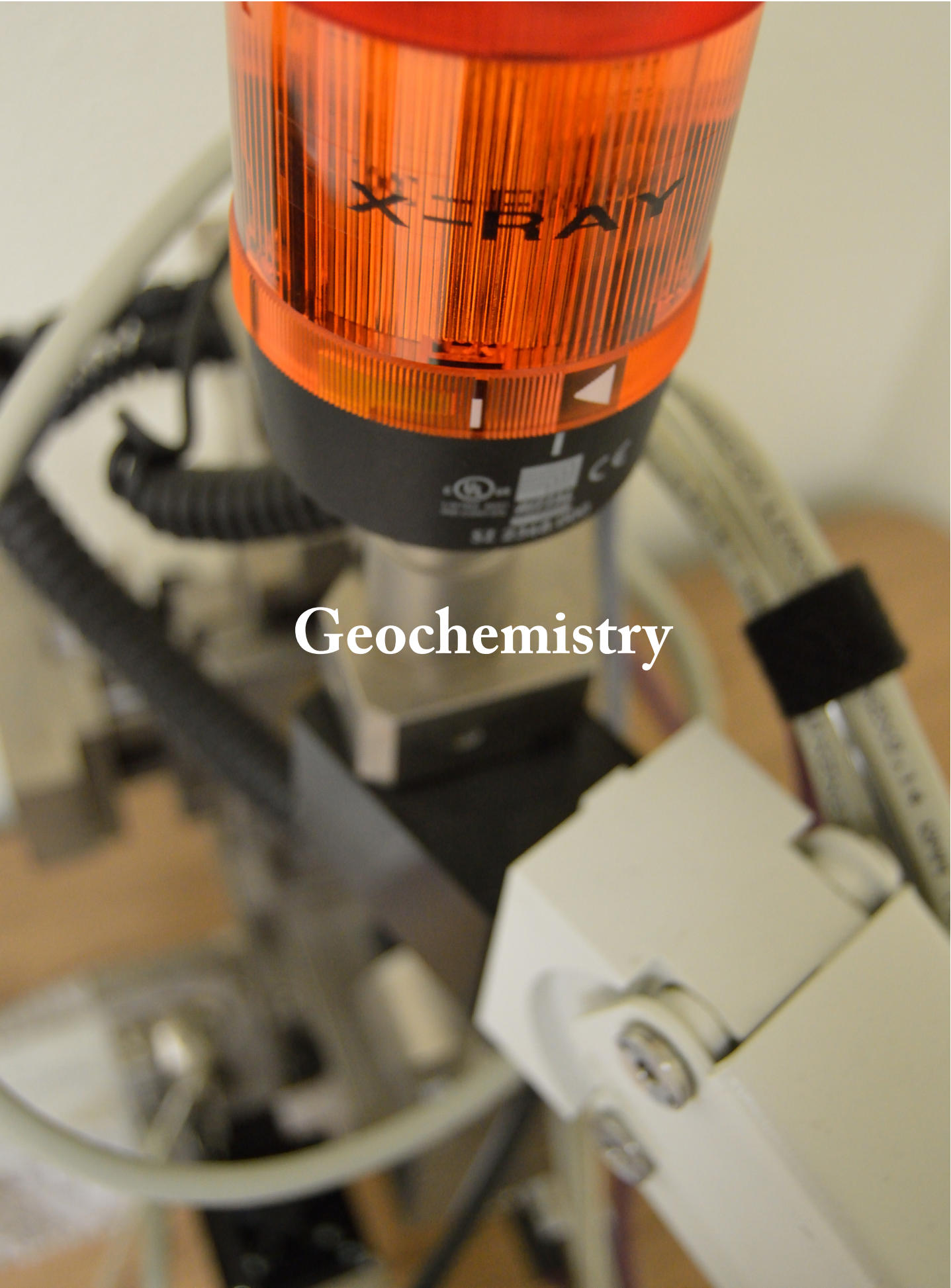
***FOCUS: DEPOSITIONAL ENVIRONMENTS
OF MUDROCKS AND APPLICATION OF GEO-
CHEMISTRY TO REFINE DELINEATION OF
FACIES IN THESE INSCRUTABLE ROCKS.***

**Characterization of Geochemical Facies in Lower
Permian Basinal Mudrocks, Midland Basin**

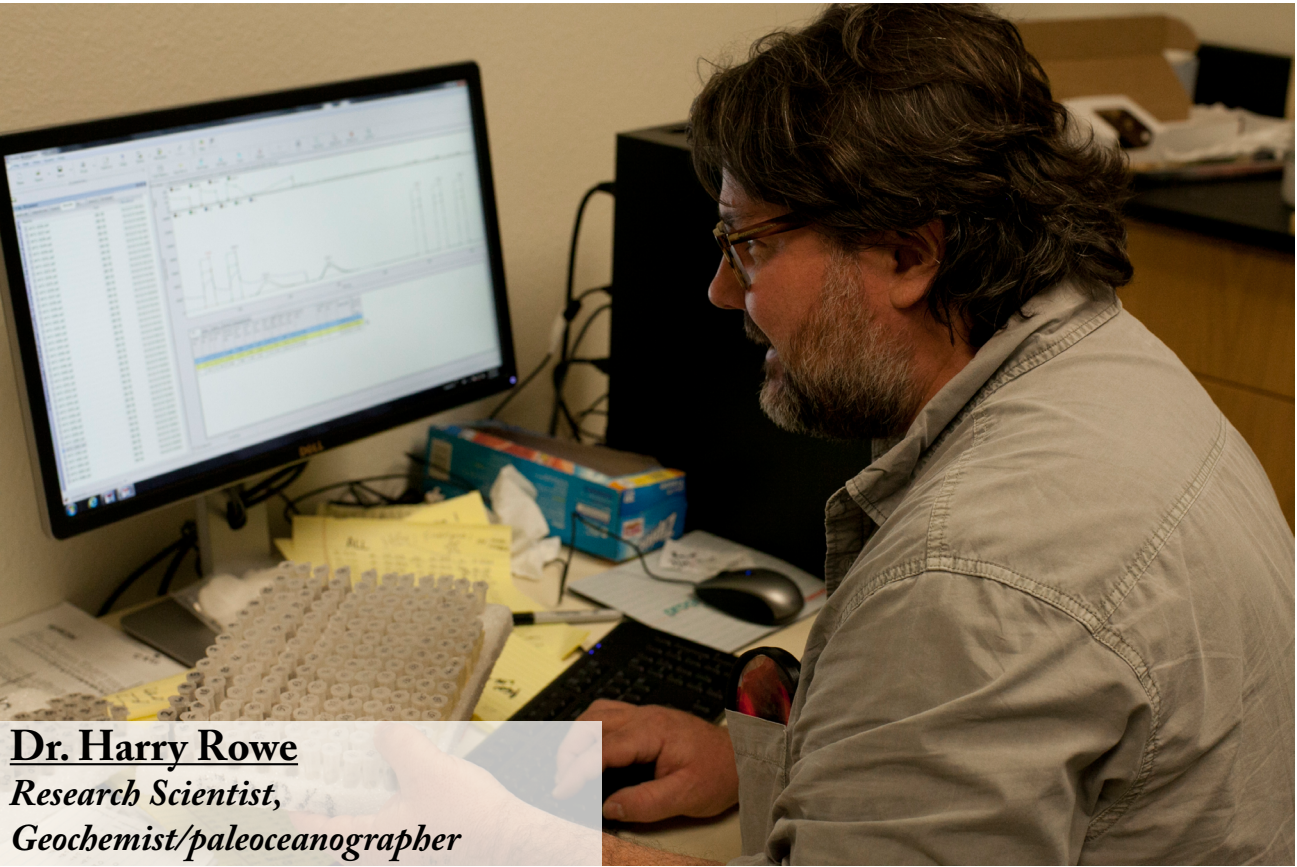
Cores in the southern Midland Basin penetrate zones that are targeted for horizontal completion in the Wolfcamp A and B. ED-XRF and XRD analyses have provided a basis for defining basic facies types, but further study is warranted to make full use of detailed geochemical data. For example, we expect cluster analysis of 28 major and trace elements will make it possible to delineate geochemical facies that are otherwise unidentifiable. The goal of this work is to enhance understanding of the paleo-geochemistry of the Midland Basin, as well as present-day, highly variable TOC concentrations.



Fine-grained, dark mudrocks are notoriously difficult to describe using heretofore conventional techniques. Calibrated high-resolution XRF analysis provides the means for defining facies based on geochemical differences that are not otherwise detectable. However, finding meaningful patterns among the possible combinations of 25+ major and trace elements is daunting. To solve this problem cluster analysis is used to find naturally-occurring associations between elements and sort them into related groups. Then, clusters are interpreted in a geochemical context, put into a stratigraphic framework, and incorporated with other data, including TOC and rock strength. The net result is a refined understanding of changes in geochemistry, organic matter content, and rock strength over small and large stratigraphic intervals.



Geochemistry



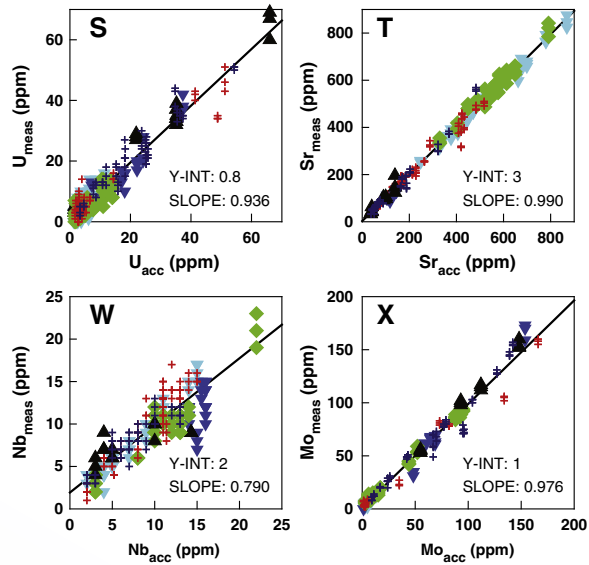
Dr. Harry Rowe
*Research Scientist,
Geochemist/paleoceanographer*

FOCUS: GEOCHEMISTRY, PALEOCEANOGRAPHY, CHEMOSTRATIGRAPHY, ISOTOPIC GEOCHEMISTRY.

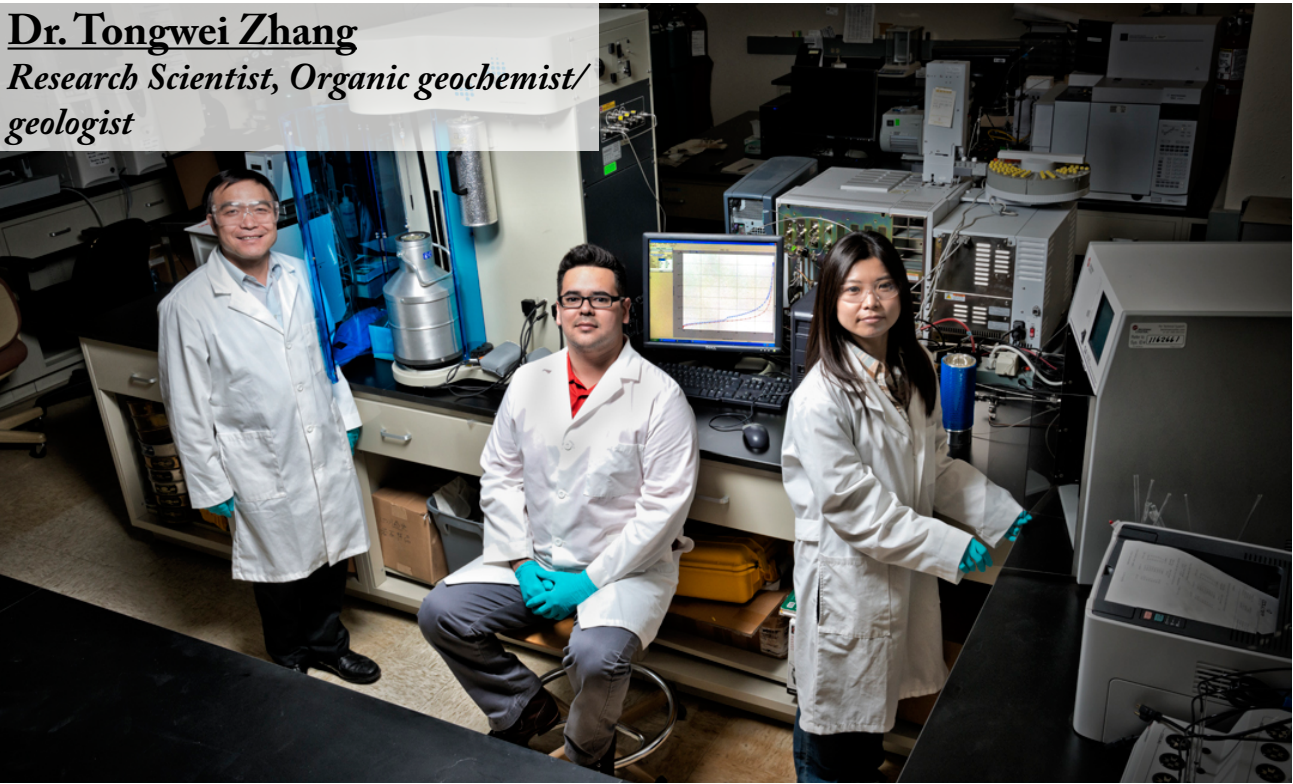
This year's focus will be on the Eagle Ford and Bakken systems. I plan to synthesize elemental and isotopic records of early late Cretaceous units (Del Rio, Buda, Eagle Ford, Austin) from South and East Texas, and place them in the context of records from the Western Interior Seaway, the deep Atlantic, and the Mediterranean. The regional integration will focus on highlighting differences between chemostratigraphic records and their underlying geological significance. The depositional conditions on large portions of the South Texas margin are thought to have been predominantly oxic during much of the Oceanic Anoxic Event #2, making an interesting contrast between the regional record and other published records from Colorado, the Arctic, the Atlantic, and the Mediterranean.

We have developed approximately twenty-five core-based chemostratigraphic records from the Bakken Formation of North Dakota and Montana. I have begun synthesizing the new results with older results from the original Brigham cores. This work will entail developing

a deeper understanding of depositional conditions, and will hopefully be assisted by organic petrography work by Dr. Sue Rimmer (Southern Illinois University). I would like to extend this work into southern Saskatchewan.



Examples of XRF measured vs. Lab tested elemental scatter plot used in handheld XRF calibration (from Rowe et al., 2012)



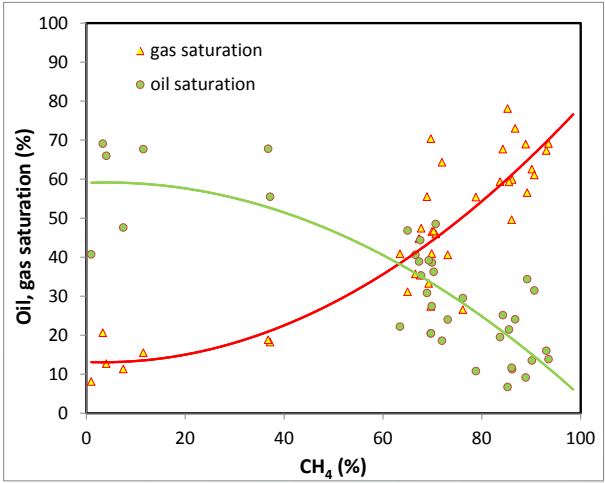
Dr. Tongwei Zhang in his laboratory (left) with Lab Technician and future grad student Daniel Enriquez (middle) and post-doctoral fellow Xun Sun (right)

FOCUS: GAS AND OIL GEOCHEMICAL CHARACTERIZATION, PETROLEUM GENERATION AND EXPULSION, HIGH TEMPERATURE AND PRESSURE GAS ADSORPTION, PORE SIZE DISTRIBUTION AND OIL/GAS STORAGE IN ORGANIC-RICH MUDSTONE.

Gas and oil saturation is an important issue for unconventional resource exploration in mudrock system. The chemical and physical processes involving in oil and gas generation, expulsion and retention can greatly affect oil saturation. Pore type, pore network, and pore size distribution determine oil and gas storage and deliverability. An integrated research between the evolution of fluid chemistry and pore development in mudrock system during diagenesis, organic matter maturation provides evidences to determine the timing of pore development associated with oil and gas generation.

The objectives of 2015 research will be: 1) to develop and design a device to measure chemical compositions of gases released from wax-coated fresh core samples, and to study the main controls on fluid composition under reservoir conditions; 2) to conduct comparative studies on pore size distribution between natural core samples

with varied thermal maturity and artificially-matured core samples, and to determine the timing of pore generation associated with oil and gas generation; 3) to conduct comparative studies of petroleum generation and expulsion between marine and lacustrine mudrock system; 4) to design the experimental system for mixing gas adsorption, and to investigate the competitive adsorption among methane and other gas components.



Prediction of Oil and Gas Saturation in Eagle Ford Formation Based on Gas Chemistry



Dr. Xun Sun
Postdoctoral fellow, organic geochemist

**FOCUS: HYDROCARBON SATURATION,
BIOMARKER FINGERPRINTING OF OILS AND
SOURCE ROCKS, PORE SIZE DISTRIBUTION**

The primary research area is in petroleum geochemistry and mudrock pore system characterization. Mass spectrometry and nitrogen absorption are used to characterize residual oil compositions from organic-rich source rock, and to analyze pore size distributions in mudrock. The goals of this research are to understand the organic

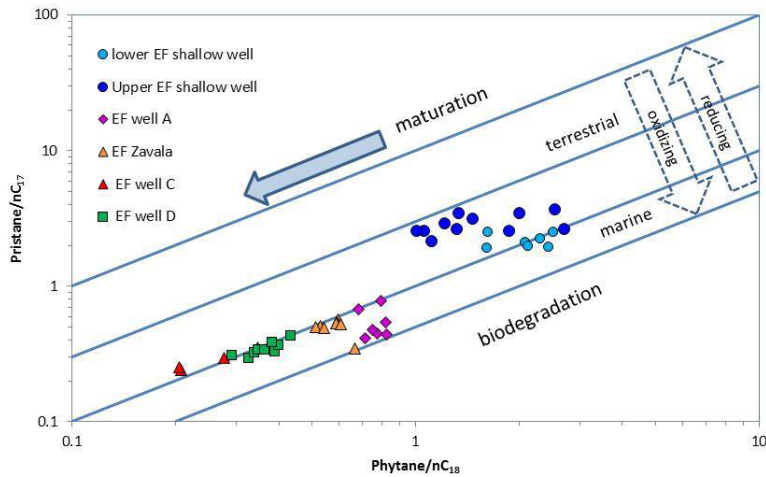
matter properties of the source rock, to determine the redox conditions of sediments, to develop biomarkers or geochemical fingerprints for oil quality and thermal maturity, and to understand processes controlling organic matter conversion, oil storage and oil expulsion in mudrock systems.

Prospective work for 2015

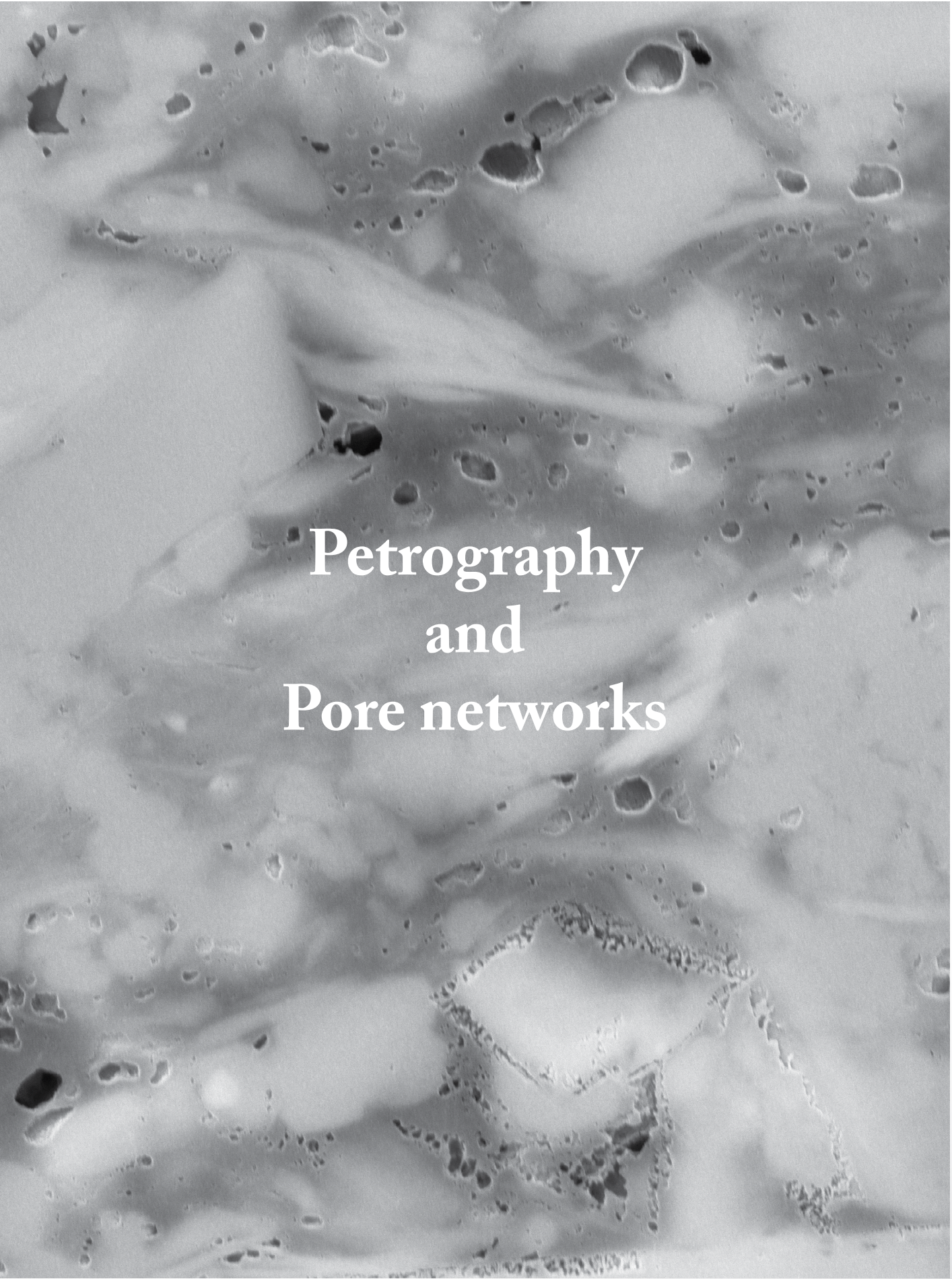
Samples from the Eagle Ford Formation with different maturity levels have been studied since 2014. More comprehensive study of Eagle Ford shale will continue in 2015, including geochemical characterization of organic matter and pore systems from low-maturity to high-maturity areas. This approach is used to determine depositional environment, thermal maturity variation, and pore development. Integrating organic geochemistry and pore character will enhance understanding of organic matter conversion, pore evolution and petroleum expulsion in Eagle Ford shale.

In addition to the Eagle Ford Formation, the Bakken Formation will be included in these studies in 2015. The same research approaches will be used for samples from six wells in the Bakken Formation. Comparing results from the Eagle Ford and Bakken will illuminate differences in organic matter conversion and preservation and pore development in carbonate-rich and clay-rich systems.

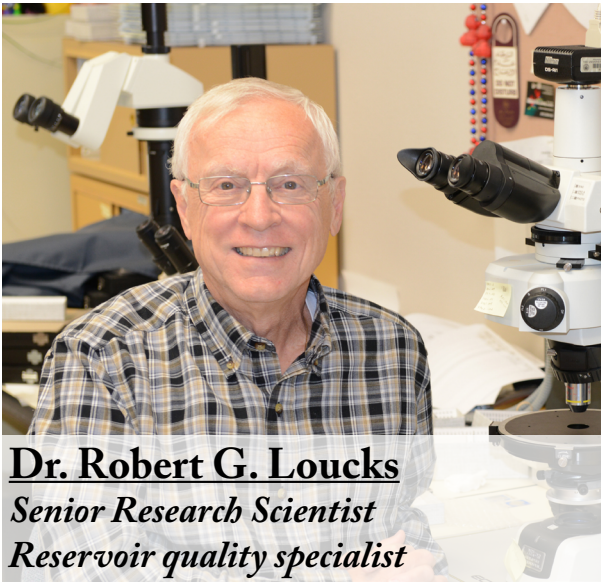
Sequential solvent extraction on different grain sizes samples of organic-rich mudrocks will be conducted, in order to gain insight into oil storage mechanism in such rocks, which relates to the different size pores.



The plot of Pristane/ nC17, Phytane/ nC18 provides the general information of the maturity, redox conditions and organic matter types of the samples from the Eagle Ford formation. The organic matter source of Eagle Ford is dominated by marine source; data of shallow well samples indicate the upper Eagle Ford shale is more oxidizing than the lower Eagle Ford. The maturities of the samples from these five wells are increase with the burial depth, which is shallow well < well A < EF Zavala < well C < well D.



**Petrography
and
Pore networks**



Dr. Robert G. Loucks
Senior Research Scientist
Reservoir quality specialist

FOCUS: MUDROCK PORE NETWORKS, MUDROCK DEPOSITIONAL SYSTEMS AND SEDIMENTOLOGY, MUDROCK DIAGENESIS

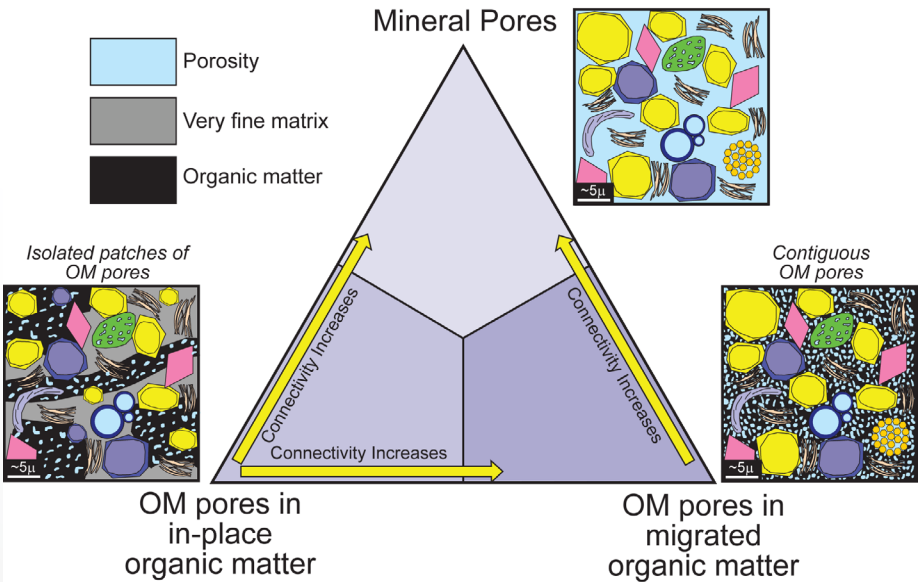
The researchers in the MSRL group were the first to document the pore networks in Barnett mudrocks, the first economic shale-gas field. Our initial research discovered organic-matter (OM) pores as well as associated mineral pores. We pioneered the Ar-ion milling technique to prepare mudrock surfaces for imaging pores. Our mudrock pore classification is widely accepted. We are broadening our research efforts into understanding the origin of mudrock pores and how they evolve dur-

ing burial (with time, temperature, and pressure). Our major objective is to understand the controls on mudrock pores and develop models to predict their distribution and quantity.

Specific objectives are to (1) understand the evolution of pores from immature mudrocks and how they change through thermal maturation with depth (2) experimentally produce the evolution of OM pores by maturation experiments on immature mudrocks, (3) understand the types of OM pores and how they evolve in kerogen versus migrated organic matter such as bitumen or pyrobitumen, (4) quantify the effects of pore types on permeability, (5) relate pore types and reservoir quality to mineralogies, microfabrics, and textures in mudrocks, and (6) investigate how pore networks may vary within and between specific mudrock lithofacies.

A major part of our effort is to integrate our concepts of mudrock pore networks into other MSRL investigations such as up-scaling pore networks from submillimeter samples to core plugs, cores, and reservoirs and to integrate our results with reservoir-fluid-flow research.

To conduct this research we are using a field-emission scanning electron microscope (SEM) that can image pores down to a range of 2 to 5 nanometers and we have several milling devices to prepare SEM samples. MSRL also has a SEM photomicrograph archive of several thousand images of mudrocks and associated pores. This archive covers many of the economic mudrock systems in the United States.



Ternary diagram showing end members (with schematic representations) of mudrock pore networks. Pore network can be combination of mineral pores, OM pores in depositional organic matter, and OM pores in migrated organic matter.

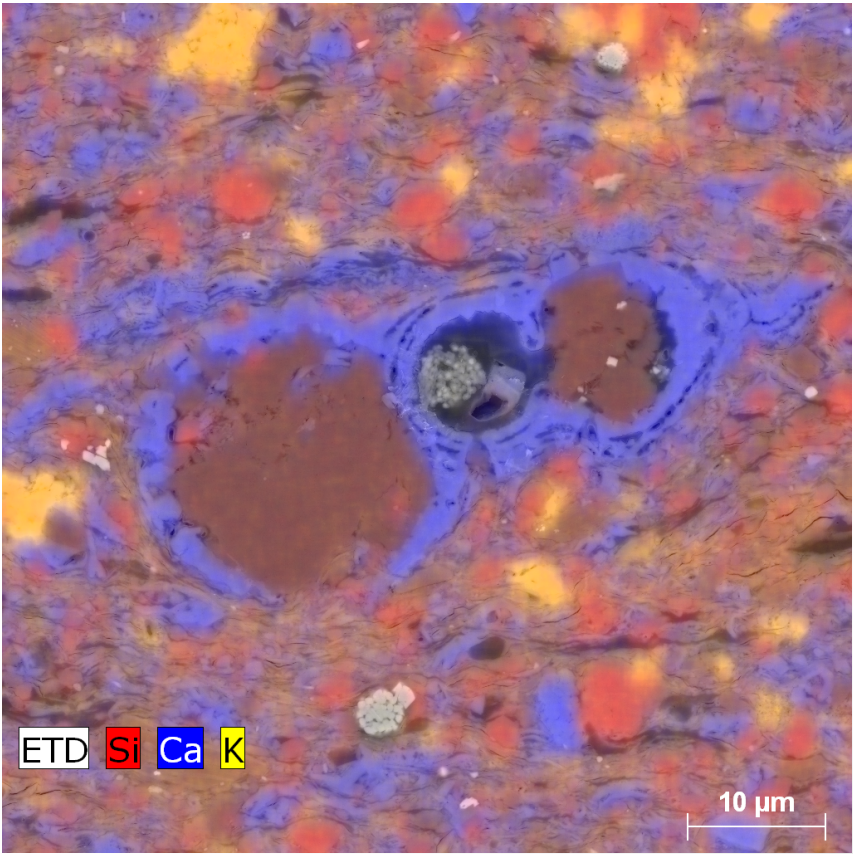


Dr. Kitty Milliken
Senior Research Scientist, Petrographer

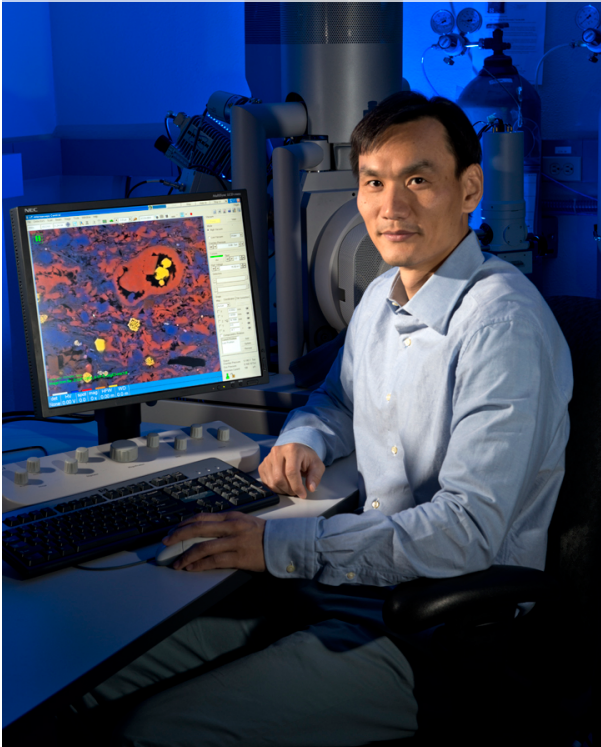
FOCUS: CHEMICAL AND MECHANICAL HISTORY OF MUDROCKS AS DECIPHERED FROM INTEGRATED PETROGRAPHIC AND CHEMICAL DATA.

Research Objective: How does the composition of the primary detrital grain assemblage in muds affect the evolution of bulk rock properties such as porosity, permeability, and mechanical moduli? What processes (cementation? compaction?) are responsible for pore modifications in mudrock diagenesis and under what conditions to these occur? Answers to these questions may allow us to create predictive models for reservoir quality in mudrocks, especially in the case that variations in detrital composition can be related to units mappable by log signatures within the overall basin stratigraphy. Currently seeking rock units and collaborations with stratigraphers to test this hypothesis

Energy dispersive X-ray spectroscopy map of a sample from the Eagle Ford Formation



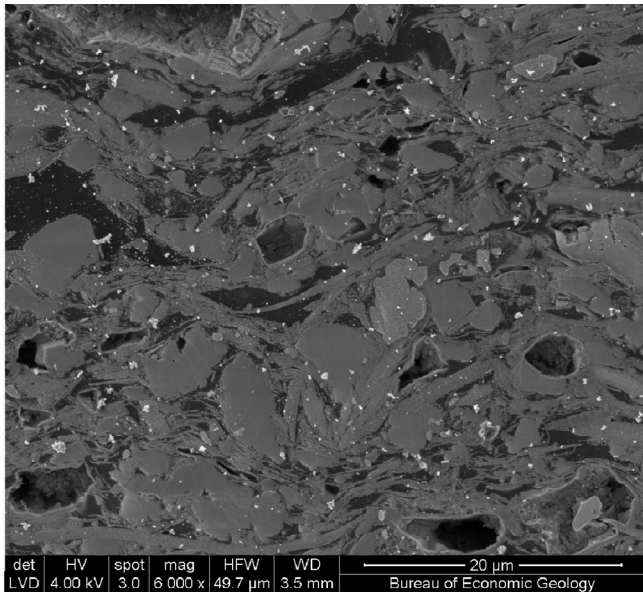
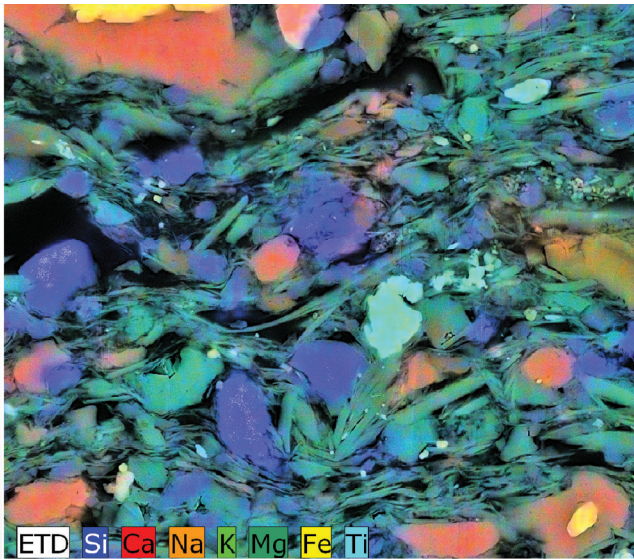
Dr. Jiemin Lu
Research Associate
Petrographer/geochemist



**FOCUS: DIAGENESIS, PETROGRAPHY, AND
ROCK-FLUID GEOCHEMISTRY.**

2015 Research Objectives

Changes of porosity and permeability beyond the rock-water interface resulted from shale-fracking fluid reactions need to be visualized and quantified in order to evaluate the effects on fluid flow during production. SEM analysis is effective to observe and quantify secondary porosity at shale surface. However, change of porosity inside the shale samples cannot be directly observed by SEM. Consequently, we cannot know how far mineral reactions would occur beyond the fracture surface. Micro-CT and focused ion beam (FIB)-SEM will be of great value to visualize and compare the pore networks before and after rock-water interaction. The thickness of the reaction zone with enhanced porosity and permeability can be examined. With the information, a better understanding of fluid flow from rock matrix into fractures can be obtained. We seek funding opportunities from MSRL sponsors to support our research on this topic.



SEM observation of mineral reactions in a three-week shale-fracking fluid reaction experiment. Pre-reaction EDS elemental map (left) showing mineral distribution at the ion-milled surface. Post-reaction SE image (right) showing dissolution pits from calcite dissolution and precipitated materials.

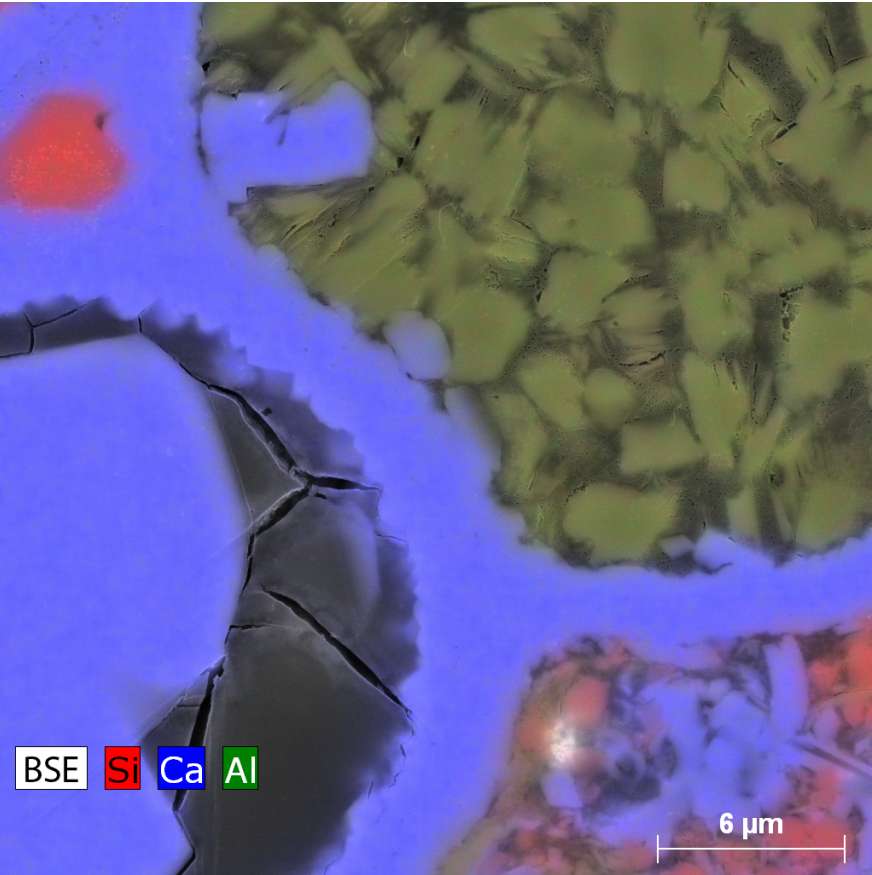


Dr. Robert M. Reed
Research Scientist Associate, Structural
geologist/nanostructure specialist

**FOCUS: MICROFABRICS OF MUDROCKS
INCLUDING PORES, CEMENTS, AND MICRO-
FRACTURES**

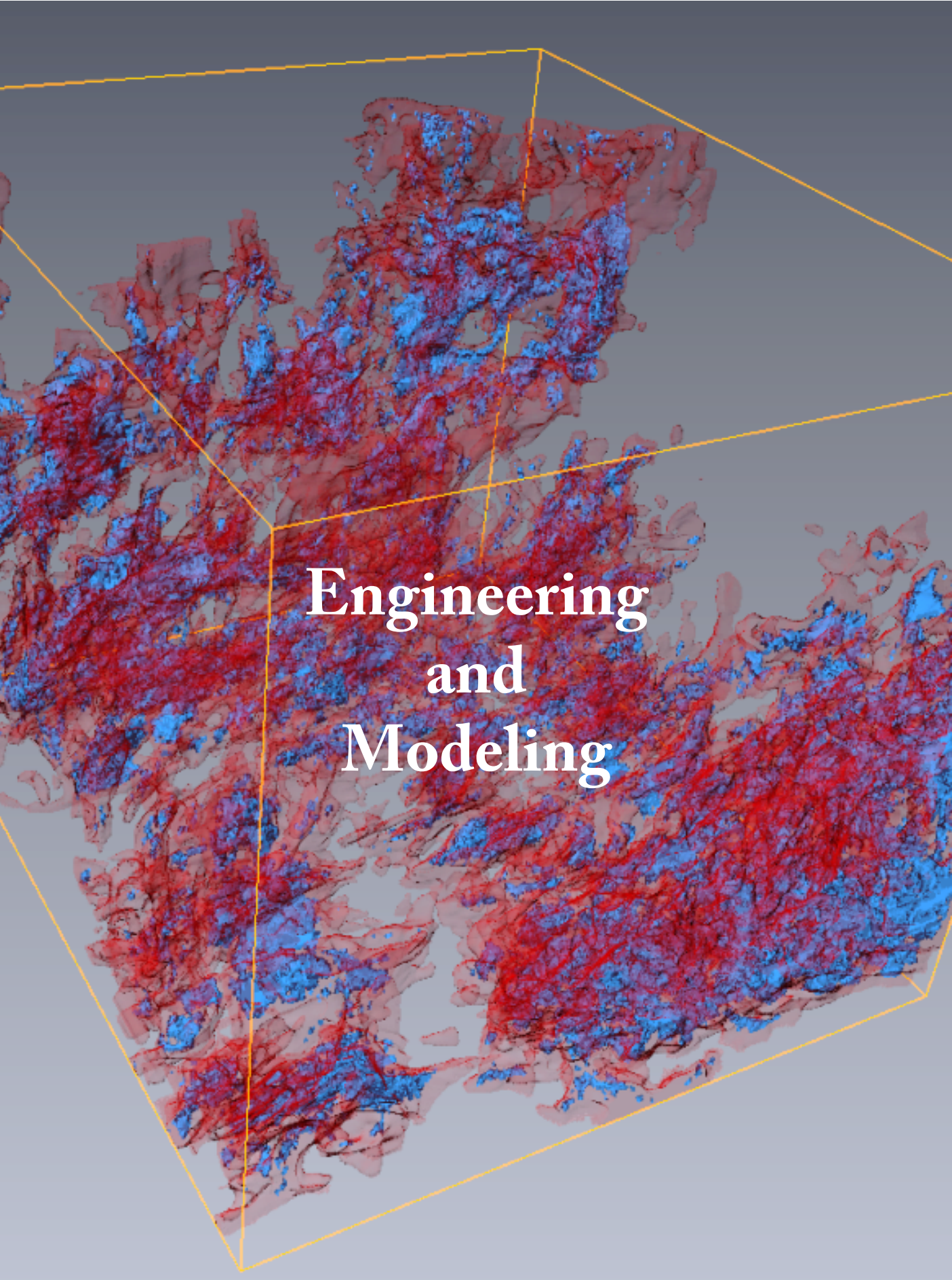
One of the remaining important unresolved questions about organic matter pore systems, is why some organic matter in thermally mature mudrocks has pores and some does not. This discrepancy is present both within samples and between samples. Understanding the possibly multiple reasons for this is an important research question we hope to address. One research approach will be looking at the distribution of sulfur and oxygen in organic matter and how that may be influencing pore development.

Additional pore research will focus on identifying pores in terrestrial kerogen that are inherited from the original plant material. Low thermal maturity organic-rich mudrocks from the Bureau's core collection will be examined as part of this research.



Combined energy dispersive spectroscopy element map and backscattered electron image of fill inside a foram from the Eagle Ford Fm. Dark material is organic matter (probably bitumen), which contains nanopores where associated with kaolinite (green) and no nanopores where associated with calcite (blue).

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Engineering and Modeling

Dr. Farzam Javadpour

Research Scientist, Flow engineer and modeler



Dr. Farzam Javadpour (top left, back) and Dr. Samira Enayati (bottom right, front) in his Atomic Force Microscope laboratory.

FOCUS: FUNDAMENTAL AND APPLIED STUDY OF FLUID FLOW PROCESSES IN SHALE GAS SYSTEM.

Slip liquid flow and apparent liquid permeability in shale.

The process of fluid loss during hydraulic fracturing and production of liquid hydrocarbons from shale strata are of immense importance in shale gas development. We have started a fundamental study of liquid flow in shale in the past two years and have accomplished important findings. We have presented the process of slip flow that can improve the flow of liquids in tiny pores of shales. We developed a new form of permeability named “apparent permeability”. Apparent permeability is an extension to Darcy permeability that includes slip length. We have shown how to measure slip length for shale and liquid of interest. We plan to continue our efforts in two paths:

- A stochastic model to get apparent liquid permeability based on SEM images.
- Fracture simulation sensitivity studies. If we receive field data, possibly try to match field data with

simulation results. Collaboration with Dr. Mark McClure from PGE.

Molecular dynamic study of liquid content and transport in liquid-rich shale system.

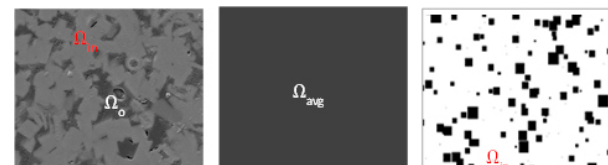
The nature of liquid flow in shale oil systems is to be studied with a molecular dynamic simulation. We plan to develop a model to accurately estimate recoverable oil-in-place and possible enhanced oil recovery methods for such systems.

A stochastic permeability model based on pore size distribution, TOC, and SEM images.

We have recently developed a rigorous stochastic model to link different forms of pores and their network measurements in a robust stochastic model to determine permeability. In our model we related kerogen patch sizes from SEM images and pore size distribution from Nitrogen and capillary pressure tests. We plan to develop a new version that includes gas desorption to determine permeability from SEM images, Nitrogen (N₂) tests, and Mercury (Hg) injection tests. We need SEM images, N₂, Hg, Langmuir isotherm, porosity, permeability, TOC data of the same samples. We will use all these data to build our model to determine permeability and to compare with the measured permeability.

Three-dimensional (3D) permeability from two-dimensional (2D) SEM images.

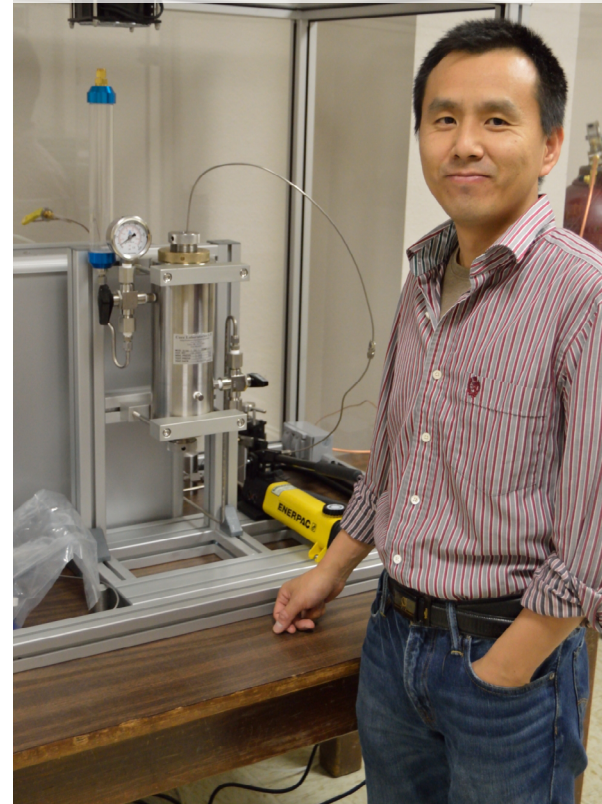
In the past few years researchers gathered many SEM images for the shale samples. One of the important petrophysical properties are the pores and permeability of the shale samples determined from SEM images. The information from the SEM images is very useful. However, determination of three-dimensional (3D) permeability is of great interest. We are developing new techniques to construct 3D realizations from 2D SEM images. We also plan to use stochastic 2D realization (as described in Item 3) to create 3D realizations.



(a) A scanning electron microscope (SEM) image from a shale sample, (b) average model that uses in most permeability models, and (c) our stochastic model for permeability. Ω_o and Ω_{in} denote organic matter and inorganic matrix.

Dr. Sheng Peng

Research Associate, Petrophysicist



FOCUS: POROSITY, PERMEABILITY, PORE NETWORK, AND PORE-SCALE PROCESSES.

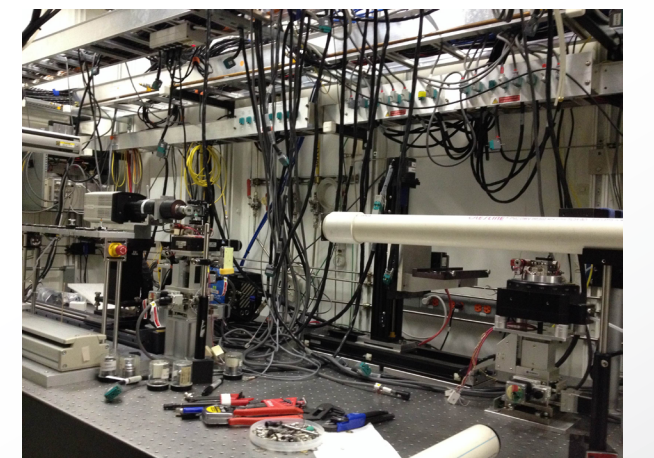
Permeability measurement for shale rocks with a modified GRI-type method incorporating overburden stress

Permeability is one of the most critical parameters for shale reservoir characterization, but its measurement remains a major challenge. Comparing to traditional pulse decay method which usually takes >24 hrs for one measurement, GRI (Gas Research Institute) method can provide much easier and faster measurement for shale permeability (<1 hr for one measurement); however, the shortcomings of GRI method include the lack of overburden stress, the lack of Klinkenberg correction, and no standard analytical expression for permeability calculation. In this on-going project, the traditional GRI method is modified to incorporate overburden stress, and an analytical solution was adapted for the permeability calculation. In addition, Klinkenberg effect is considered in low pore pressures. This modified GRI-type method can provide an easier and faster way for better estimation on in-situ permeability. On the other hand, whether there are induced sub-micro scale fractures and how they

contribute to the measured permeability is under debate, partly because of the complication caused by sample preparation and the difficulties in direct observation of the sub-micron scale fractures in the plug-scale samples. In this project, permeability is compared between crushed and plug samples to investigate the presence of sub-micro-fractures and how they contribute to the apparent “matrix” permeability.

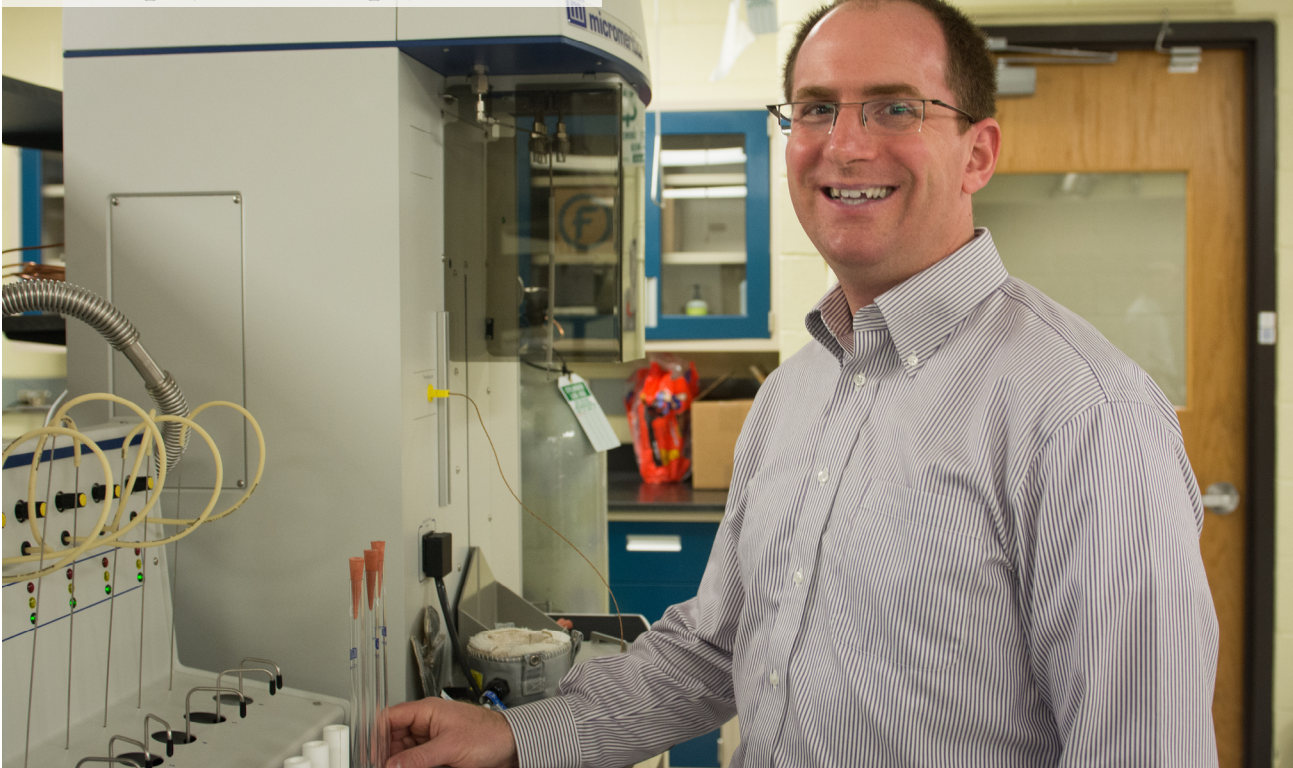
Dynamic nano-CT imaging under high pressure-temperature conditions to investigate pore and organic matter evolution for shale rocks

One major challenge in studying shale oil and gas is to characterize nano-pore and organic matter networks at relevant pressure-temperature (P-T) conditions of the geological formations. Various imaging techniques have been employed for such characterizations; however, most of these experiments had been conducted at ambient or vacuum conditions. In situ nano-scale imaging for shale rocks at high P-T conditions remains scarce and thus highly desirable. Moreover, in-situ high P-T imaging can provide new insights into the time-dependent (t) evolutions of the pore and organic matter in shale rocks. In this proposed project, we will conduct in-situ nano-CT imaging experiments for Barnett Shale at P-T conditions that mimic the real geological condition. Samples with different organic matter type and porosity will be examined to evaluate their influences on pore evolutions. Quantitative analyses on pore and organic matter size, shape, number, connection, and permeability will be conducted based on the tomographic images. From this work, we will address questions such as what is the influence of P-T-t on pore-scale imaging, how the pore and organic matter networks develop during geological burial history, how bitumen migrates and produces an extended permeability system.



Micro-scale characterization of shale by synchrotron micro-CT scan.

Dr. Hugh Daigle
Assistant professor, Petrophysicist



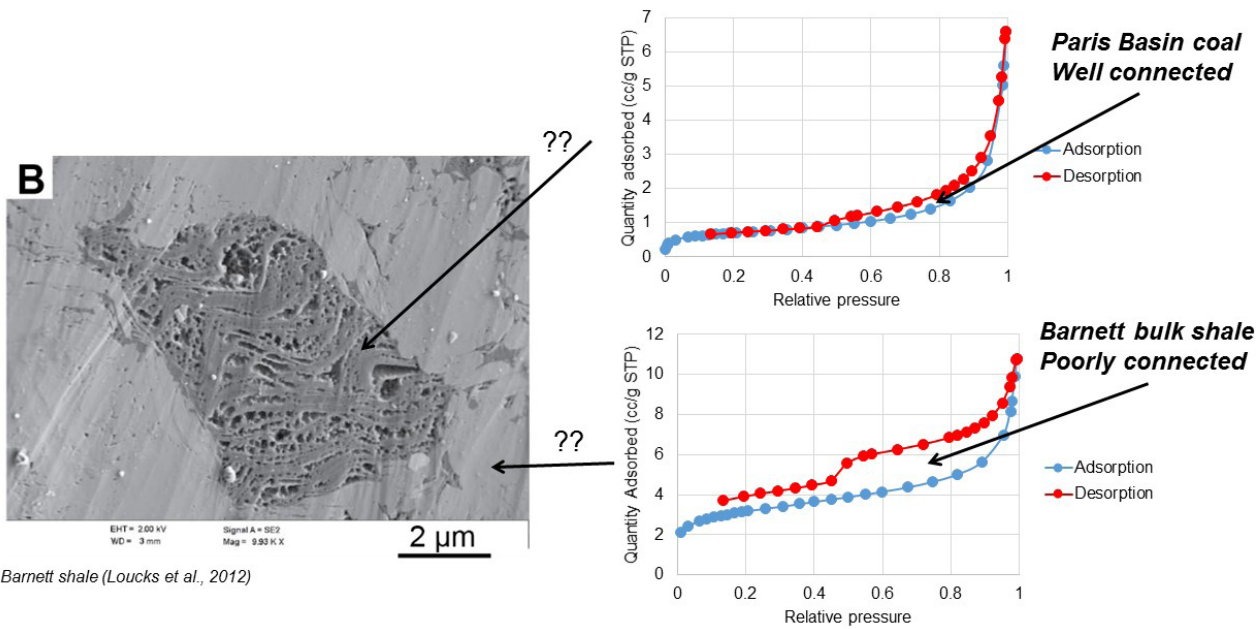
FOCUS: PORE NETWORKS, PETROPHYSICS

Pore size and connectivity of the inorganic and organic components of shales

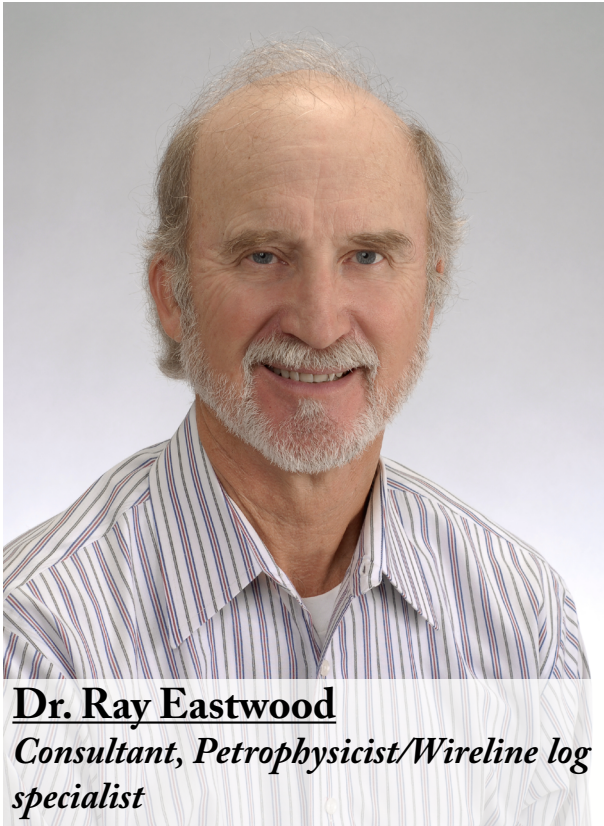
This new project will focus on determining pore size and structure in isolated organic and inorganic components of shales using low-pressure argon adsorption/desorption isotherms. Adsorption/desorption hysteresis loops may be used to characterize pore connectivity, and we will seek to perform measurements on chemically separated organic and inorganic components of shales in order to gain a better understanding of how fluids move through the different pore systems. Our laboratory measurements will allow us to gain information on pores that are much smaller than those resolvable using imaging techniques like SEM, and will allow us to determine the true, three-dimensional connectivity of the pores.

Nitrogen adsorption/desorption isotherm hysteresis has been used extensively to characterize pore sizes and connectivity in a variety of geological and industrial materials, but the minimum pore size limit of nitrogen measurements (~1 nm) limits its applicability in shales. CO₂ adsorption may be used to characterize sub-nm sized

pores, but adsorption of CO₂ in organic-hosted pores raises the possibility of chemical interactions between the CO₂ and organic matter. Argon is an attractive alternative since it may be used to characterize adsorption/desorption hysteresis, similar to nitrogen; can be used to characterize sub-nm sized pores, similar to CO₂; and is nonreactive with substrates. We will start our initial work using well-characterized Eagle Ford samples and seek input for additional samples to test.



Possible differences in connectivity illustrated with SEM image of Barnett shale. The organic-hosted pores (spongy texture in the dark organic particle) may have better connectivity than the inorganic matrix. This is illustrated by two nitrogen adsorption-desorption experiments: one from a Cretaceous coal from the Paris Basin (upper plot) and one from a bulk sample of Barnett (organic + inorganic components together). The degree of connectivity is manifested in the separation between the adsorption (blue) and desorption (red) curves, with more separation corresponding to lower degrees of connectivity (i.e., lower coordination number).



**FOCUS: PETROPHYSICS, LOG BASED MODEL-
LING, INTEGRATION OF ROCK DATA**

I propose to continue MSRL Petrophysical investigations along previous lines; namely, 1) testing/ improving log model results for shales for a few old and whatever additional wells are appropriate and 2) investigation of MICP results for shale samples, as available. I continue to examine the literature for forward models that might be useful in computation of mechanical properties.

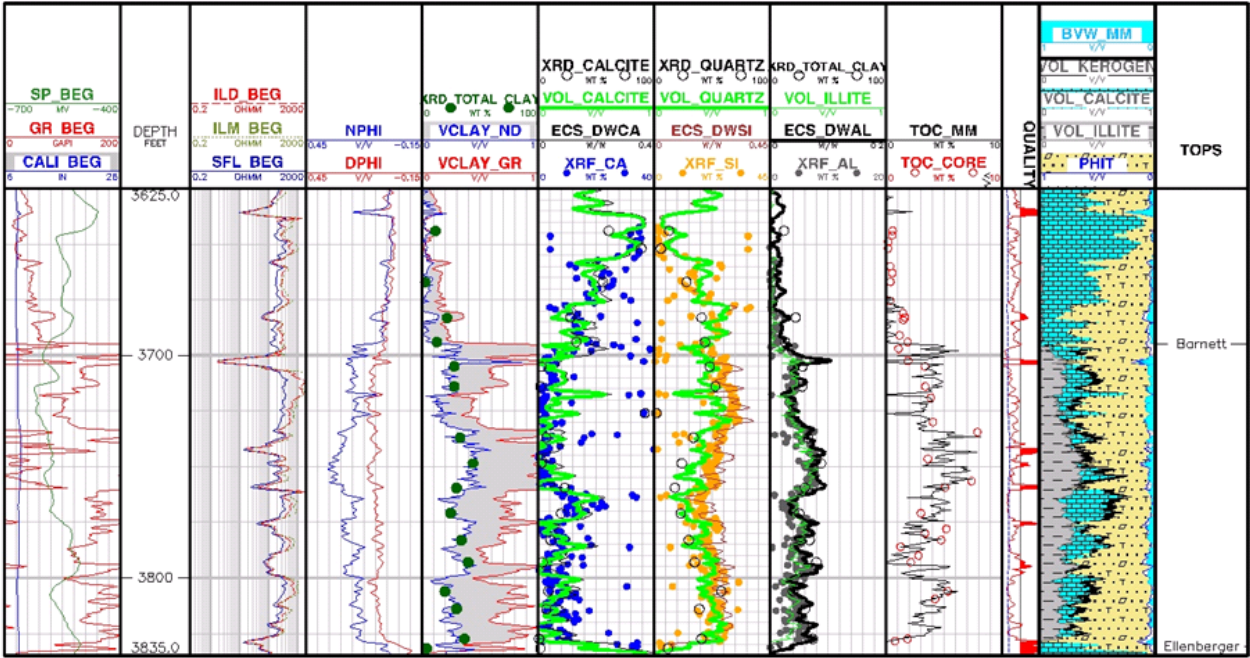
Testing/improving log model results

We want to continue application and testing log interpretative models for unconventional reservoirs. This includes wells having adequate logging data for the Barnett, Eagle Ford, Woodford, Haynesville and other shales as they become available. Integration of XRD and XRF data, as available from core, is a central part of this investigation and serves to benchmark log model results. Comparisons of log model results should be made against core data, as available.

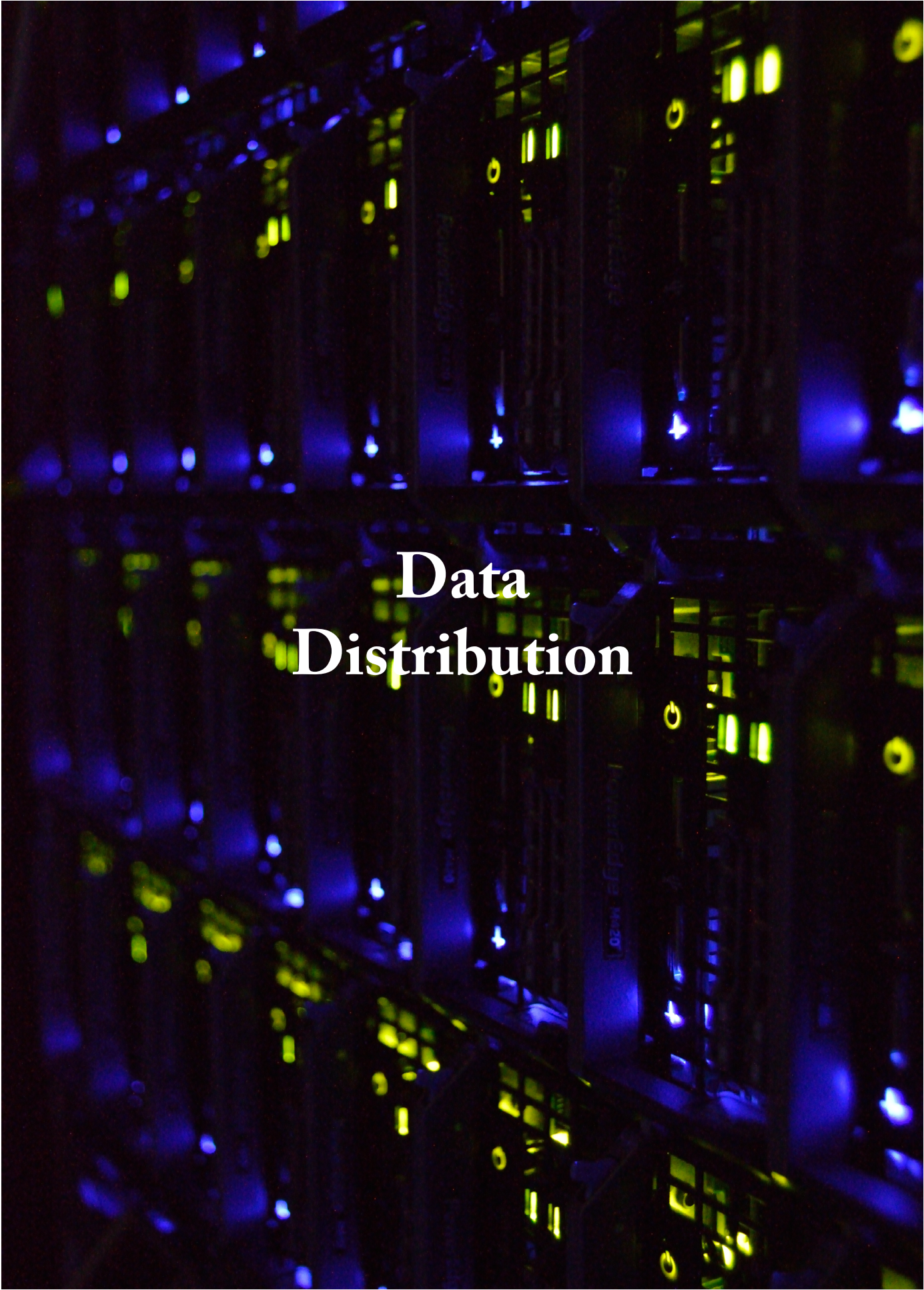
Investigation of MICP results

We will continue to investigate pore throat size distributions of unconventional reservoirs by analysis of MICP data. This includes data from the Barnett, Eagle Ford, Woodford, Haynesville and other shales, as they become available. We look forward to expanding our MICP database.

Well: Mesquite #1



Comparison of Barnett Log Model Results and Core Data for the Mesquite #1





Cari Breton B.A.
Research Scientist Associate, GIS and database specialist

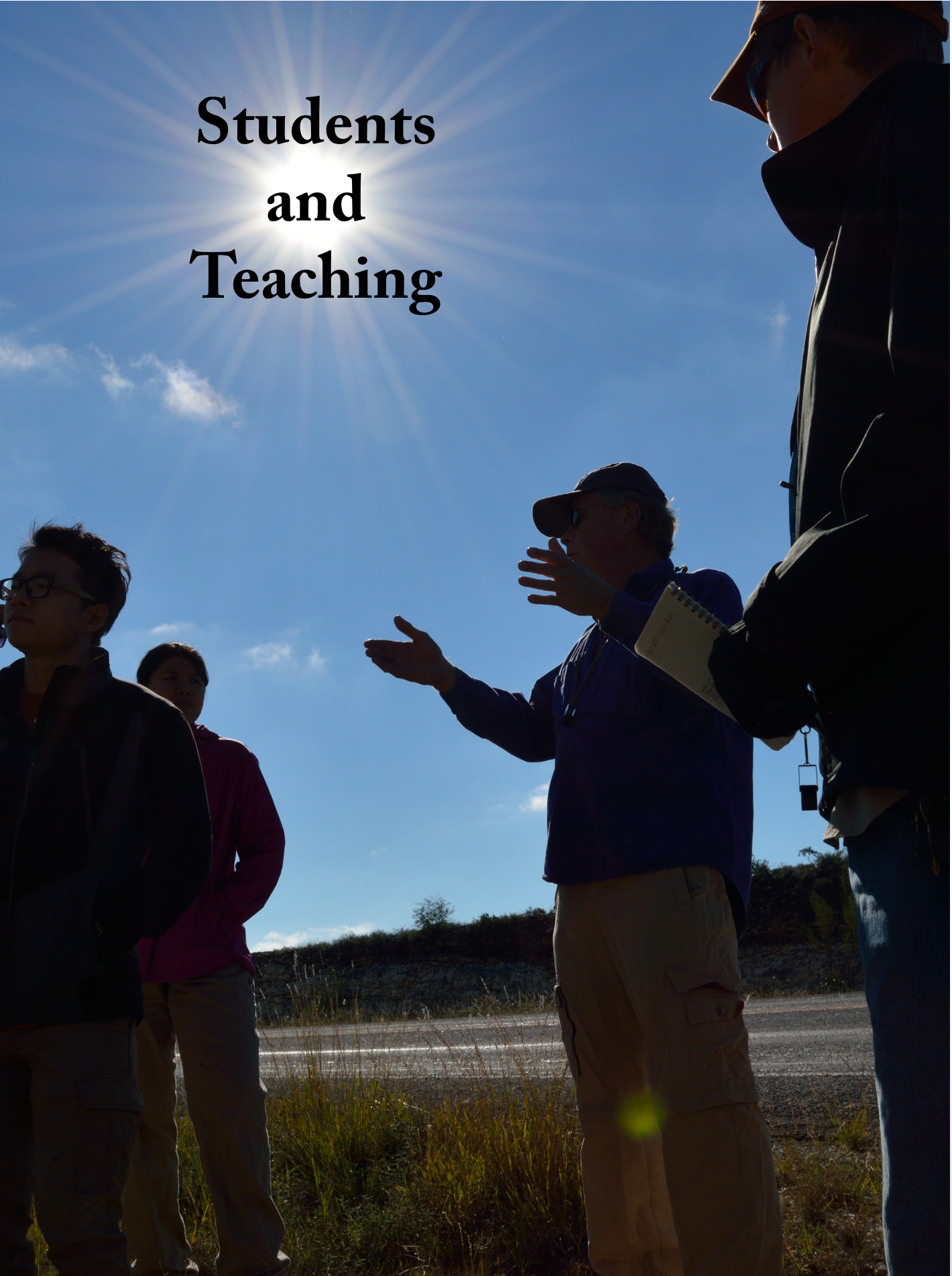
FOCUS: DATABASE AND WEB SITE MANAGEMENT, GEOGRAPHIC INFORMATION SYSTEMS (GIS)

The materials produced by MSRL's multidisciplinary research team are voluminous. With every year come new publications, posters, presentations and workshops. These materials are updated regularly and made available through the MSRL member's website. Prior to the yearly MSRL meeting a large amount of data is collected from the team for distribution to members. This effort has been moved online to facilitate access by MSRL members. As of April 6th 8212 files (60.3 GB) have been organized, catalogued and made available for download.

The database and website are organized primarily by formation, county then well. Data types include biostratigraphy, core description, core photos, fluid flow and pore systems, geochemistry and mineralogy, maturity and rock mechanics, organic geochemistry, outcrop photos, rock imaging, source rock analyses reports, stratigraphy, type logs, and thin section photos. The structure and content of the database are described in an Excel workbook file. The Excel file contains a master well list sorted by formation and API showing basic header information and available data types. A straightforward approach to the data directory and website organization allows maximum control and efficiency to the end user and ensures flexibility moving forward. Feedback from MSRL members regarding use of the website and treatment of the data is strongly encouraged.



MSRL project database access page



Lucy Ko
Ph.D. Student



FOCUS: IMAGING AND EXPERIMENTAL ANALYSIS OF ORGANIC MATTER AND PORE EVOLUTION WITH MATURITY

Pore evolution of organic-rich mudrock

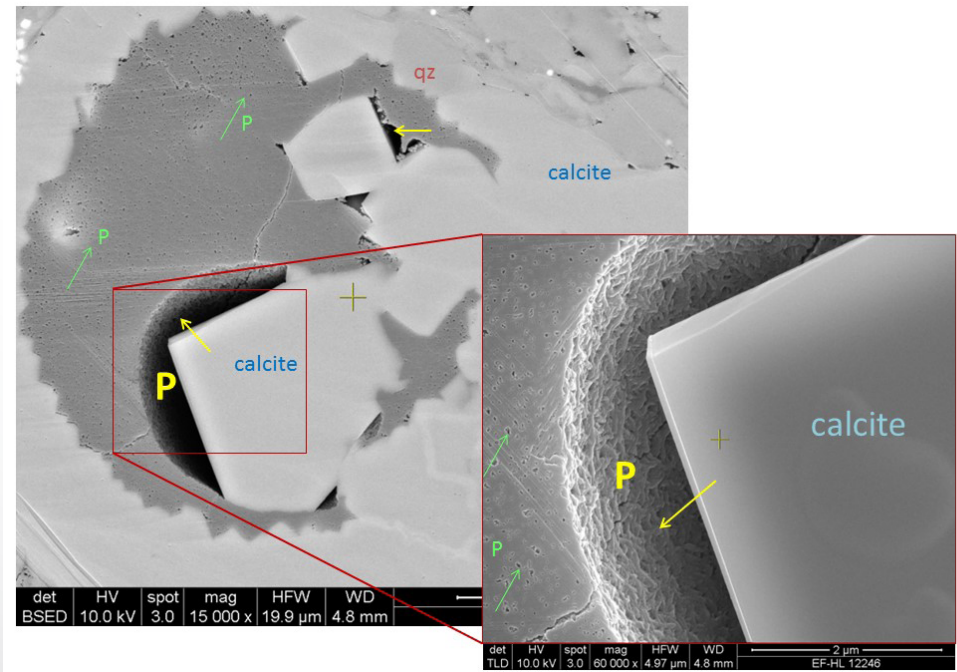
This study investigates the evolution of the pore network using results from gold-tube pyrolysis experiments and samples from the Barnett, Boquillas, Woodford chert, and Woodford Formation

Pore characterization of Upper Cretaceous Eagle Ford mudstone

This SEM photomicrograph-based study aims to quantify shape and size of OM pores in detail. The evolution of OM pore at increasing levels of thermal maturity was observed and characterized from laboratory experiments. The characterization of OM pores in mudrock core samples provides supports of laboratory observation as well as provides quantitative description – a step forward towards future reservoir quality prediction and fluid flow modeling in mudrocks.

Variation of OM pores and mineral pores of the Lower Cretaceous Pearsall mudstone.

This study aims to integrate depositional, mineralogical, and thermal controls on pore type variation along the dip direction. The integration of depositional and mineralogical controls on mineral pores along the dip direction adds significant values to a play-scale pore prediction in a carbonate-mudrock mixed system.



Micron-sized combination pores (yellow arrows) and nanometer-sized OM pores (green arrows) in the organic matter inside the foraminifera in the Eagle Ford mudrock.

Ahmed Alnahwi (degree pursued: Ph.D.)

Pore pressure and geological controls, Eagle Ford Formation.

Geochemistry, mineralogy, sedimentology, petrography, reservoir characterization, well logging, Eagle Ford Formation.

Jesse Berney (degree pursued: MS)

“Three-dimensional variability in the Bakken Formation, Williston Basin, ND.”

Mudrocks, geochemistry, mineralogy, sedimentology, Bakken Formation.

Daniel Enriquez (degree pursued: MS)

“Carbon Isotope Characterization of Released Gases in Rock Crushing and Implication to Thermal Maturity and Ultimate Gas Recovery.”

Carbon isotopes, shale gas, rock crushing, thermal maturity, gas storage.

Kathryn Fry (degree pursued: MS)

“Lithofacies and Chemostratigraphy of the Boquillas and Eagle Ford Formations: A Comparison of Outcrop and Core data from Big Bend National Park to Maverick Basin, Southwest Texas, USA.”

Stratigraphy, biostratigraphy, geochemistry, Eagle Ford Formation.

Kyle Gabb (degree pursued: MS)

“High resolution, close proximity chemostratigraphy and lithofacie analysis of subsurface late Cretaceous aged formations of Central Texas.”

Geochemistry, mineralogy, reservoir potential, Eagle Ford Formation.

Hector Garza, (BSc, intern)

“Study of Small Scale Elemental Lateral Variability In The Eagle Ford Formation Using Ultra-High Frequency Hand Held X-Ray Fluorescence (XRF) Dataset.”

X-Ray Fluorescence, geochemistry, sedimentology, Eagle Ford Formation.

Ningjie Hu (degree pursued: MS)

“Stratigraphic Architecture, Depositional Systems, Lithofacies, and Reservoir Quality of A Deep-water, Hybrid Mu-

drock System: Middle Pennsylvanian (Early Desmoinesian) Cherokee Group, Anadarko Basin, Northeast Texas Panhandle.”

Sedimentology, stratigraphy, petrography, reservoir characterization, hybrid reservoir, Cherokee Group.

Justin Mauck (degree pursued: MS)

“Internal architecture and heterogeneities in the middle member of the Boquillas Formation along HWY 90, Val Verde Co.: Analogue for the productive subsurface Eagle Ford Formation”

Sedimentology, stratigraphy, diagenesis, LIDAR, GigaPan, Eagle Ford Formation.

Rita Bitar Nehme (degree pursued: MS)

“A High-Resolution Chemostratigraphy of the Late Jurassic Bossier and Haynesville Formations, East Texas, USA.”

Geochemistry, Molybdenum, Haynesville Formation, Bossier Shale.

Michael Nieto (degree pursued: MS)

“Chemostratigraphic and Tephrochronologic Record of Cenomanian-Turonian Eagle Ford, Atascosa County, USA.”

Geochemistry, geochronology, OAE2, chronostratigraphy, Eagle Ford Shale, XRF, XRD.

Lauren Redmond (degree pursued: MS)

Regional Reservoir Characterization of the Barnett Formation in the Southern Fort Worth Basin

Petrography, sedimentology, geochemistry, stratal architecture, paleoceanographic conditions, mudrock reservoir heterogeneity

Reed Roush (degree pursued: MS)

“Regional stratigraphic and core-based characterization of the Cline Shale, Midland Basin, Texas.”

Mudrock, chemostratigraphy, stratigraphy, cyclicity, Cline Shale.

James “Jake” Shutlz (degree pursued: MS)

“Eagle Ford Pore Networks Identified Through NMR Analysis”

NMR, pore networks, petrophysics, rock properties Eagle Ford Formation.

Geology of Mudrock Systems class

Since fall semester 2013, Dr. Greg Frébourg has been coordinating the GEO 391 graduate level class “Geology of Mudrocks Systems, co-taught by Drs. Steven C. Ruppel, Robert G. Loucks and himself, with the participation of Dr. Harry Rowe.

This course aims to provide the students with a theoretical to hands-on integrated, multiscale and multidisciplinary approach to these systems, resulting in a learning experience encompassing an overview of this broad topic to strong application concepts and skills.

Lectures are supplemented with practical exercises and a field trip to the Eagle Ford Formation outcrops. This course is limited to 15 participants and is designed for graduate students, though upper-division undergraduates can be accepted upon instructors’ consent. The grading is balanced between: core work presentation, critical article review, field work report, home assignments and an end of class recapitulative exam.

The field trip to the Cretaceous strata outcropping along HWY 90 has received yearly perennial funding

from MSRL sponsor ConocoPhillips. This field trip devotes one and a half day to on-site lectures about the Cretaceous systems of South and West Texas (Salmon Peak Formation, Buda Limestone, Del Rio Clay, Eagle Ford/Boquillas Formation, Austin Chalk) and their sedimentology, paleoenvironments, and significance for exploration and exploitation of hydrocarbon plays. One day is reserved to outcrop work during which students measure and describe a section in the Boquillas formation and write a report.

The lectures cover a diverse array of topics, build an up-to-date understanding of mudrocks systems from the regional scale to the nanopore scale along with geochemical, paleoclimatic, oceanographic and depositional dynamics. The topics are: regional and environmental settings of mudrock systems, sedimentology of mudrock systems: the sediment, sedimentology of mudrock systems: processes, sedimentology of mudrock systems: genetic sedimentology, geochemistry of mudrock systems (methods, techniques, elements), paleobiology of mudrock systems, reservoir characterization, application of sequence stratigraphy and use of wireline logs, diagenesis of mudrock systems, pore networks of mudrock systems.



2014 Geology of Mudrock Systems class with instructors Drs. Stephen C. Ruppel and Robert G. Loucks (Frébourg behind the camera) examining the Buda Limestone/Eagle Ford Formation contact along HWY 90, Val Verde Co. West Texas.

Laboratories, Facilities and Equipment



Equipment

To perform their research, MSRL researchers benefit from state-of-the arts specialty dedicated facilities and equipments. Recent funding has been secured to extend the laboratory building attached to the Bureau of Economic Geology, and MSRL will extend it’s lab surface in the brand new future space.

Organic and Mineral Geochemistry:

Custom-built high-pressure pure gas adsorption/desorption system

Agilent 7890A gas chromatograph

Custom rock-crusher sample cell and Spex sample prep 800M mixer/mill for use with GC system

Shimadzu GCMS-QP2010S gas chromatograph/mass spectrometer

Foss Soxtec 2043 extraction unit

Quantachrome Autosorb iQ-MP physisorption analyzer

Delta V Isotope Ratio Mass Spectrometer

BTX II Compact Benchtop X-Ray Diffraction System

6 Bruker Tracer Series XRFs

Helium Press for XRF

Costech Elemental Analyzer

Thermo Scientific GasBench II

UIC CM5015 Coulometer

SPEX X-Press Laboratory Pellet Press

Sartorius Cubis Microbalance

Nanopore Imaging and Modelling:

NextEngine 3D Laser Scanner

Ultrapore 300 Porosimeter

SMP-200 Shale Matrix permeameter

RCHR-series core holder

AIST-NT SmartSPM 1000 Atomic force microscope on Herzan TS-150 stable table

Zeiss Axio light microscope equipped with Hamamatsu ORCA-flash 4.0-C11440 high speed digital camera

Shimadzu UV-2450 particle analyser on custom-built packed column with Fractionator Frac-920 sample collector and Metzler Toledo balance

Philips XL430 scanning electron microscope

FEI NN 430 scanning electron microscope

Gatan Chroma cathodoluminescence imaging system

Bruker dual detector EDS system

Leica triple gun cross sectional ion milling instrument

Gatan 682PMP ion miller/coater

Ladd Carbon Coater

Leica EM ACE 600 metal coater

Optical microscope Nikon Labophot-pol

Petrographic Imaging:

Keyence VHX-1000 3D digital microscope

Nikon LV100N POL epi- and diascopic mineralogical microscope

2 Leica DMLSP mineralogical microscopes

5 Nikon UV Fluorescence microscopes

Field Equipment:

Optech ILRIS-LR spectral LIDAR

GigaPan EpicPro automated stand with Canon 10D camera

Radioactive Solutions RS-230 spectral gamma-ray handheld scanner

Rock Mechanics/Petrophysics:

RTR-1000 Triaxial Rock Testing system

3 Proseq Equotip Bambino rebound hammers

Olson NDE 360 UPV benchtop ultrasonic measurements system

Core Lab high resolution & frequency minipermemeter

Core Lab belt fed spectral gamma-ray whole-core scanner

Precision automated plugger drill and trim saw/sander for sample preparation

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MUDROCK SYSTEM RESEARCH LABORATORY
RESEARCH PROSPECTUS 2015

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