

Annual Report
2012

012



Bureau of Economic Geology
Scott W. Tinker, Director



BUREAU OF
ECONOMIC
GEOLOGY

Director:
Scott W. Tinker

Associate Directors
Eric C. Potter, Energy
Michael H. Young, Environmental Systems
Jay P. Kipper, Administration

Research and Administrative Office and Laboratories
J. J. Pickle Research Campus
10100 Burnet Road
Austin, Texas 78758-4445
(512) 471-1534, Switchboard
(512) 471-0320, Public Information
(512) 471-0140, Fax
(512) 471-7144, Publication Sales
1-888-839-4365, Toll-free phone (USA)
1-888-839-6277, Toll-free fax (USA)

Mailing address
The University of Texas at Austin
University Station, Box X
Austin, Texas 78713-8924

Website
www.beg.utexas.edu

Media Manager
Cathy J. Brown

Illustrator
John T. Ames

Photographer
David M. Stephens

Editor
Lana Dieterich

Designer
Jamie H. Coggin

Contents

- 1** Director's Page
- 2** Energy
- 80** Environment
- 118** Administrative Support
- 130** Honors, Awards, and In Memoriam
- 136** Publications
- 143** Bureau Finances

Director's Message

I write sitting alone in the airport in Bogotá, Colombia, at 5:30 a.m. on a Friday morning having just arrived from Houston overnight. I am waiting to catch a flight to Bucaramanga, where I will have lunch with Ecopetrol executives, speak at a technical forum broadcast to Ecopetrol offices continentwide, and then catch a flight still later today to Singapore, via Frankfurt, to arrive Sunday afternoon for the International AAPG Convention. That's right, three nights in a row on planes....



Scott W. Tinker

But I'm not out here alone! In August I saw Gürcan Gülen, Peter Eichhubl, Andras Fall, Steve Laubach, and others at the International Geological Congress in Brisbane, Australia. And in different corners of the world in August were Jeff Paine, Aaron Averett, John Andrews, and Tom Tremblay conducting a regional lidar survey near Dead Horse, Alaska; Michelle Michot Foss attending the ParlAmericas Assembly in Panama City, Panama; Martin Jackson visiting Petrobras E&P and Petrobras University in Rio de Janeiro, Brazil; and Katherine Romanak at the International Energy Agencies Greenhouse Gas Carbon Capture and Storage School at Tsinghua University, in Beijing, China. And these are examples from August alone! I often wonder what John Adams, who spent months on a single trans-Atlantic crossing, would think of our mobility.

But I believe Mr. Adams would appreciate the global exchange of science and goodwill embodied by our staff, representing over 20 nations from 6 continents. To celebrate our diversity, we are doing something different; in this Bureau Annual Report you will meet the whole family! Each researcher and each staff department has contributed a page that talks about his or her work at the Bureau. I'm not talking about boring lists of talks, papers, and awards, but instead the research, in layman's terms, capturing the individual and collaborative impact of the Bureau.

This kind of report won't come along often. I hope you enjoy it.

The Three-E Waltz

Dr. Scott W. Tinker



The Bureau has three primary research thrust areas: energy, environment, and economy. Our work building bridges between academe, government, and industry in the Three E's involves applied research



Photo courtesy of Harry Lynch

with a fundamental underpinning, results of which inform regulation and policy. Although this mission sounds straightforward, its implementation is not—in its balancing of funding between Federal, State, foundational, university, and industrial sources; its engagement at high levels with these same entities to maintain knowledge and expertise; and its independent, high-quality research, results of which are trusted across all sectors.

Fortunately, the Bureau mission fits my passion. My research interests of global energy supply and demand and associated economics and environmental impacts have led me to conclude that energy security—available, affordable, reliable, and environmental—must drive energy policy; efficiency and diversity are key elements. Ultimately, energy security requires a reasoned balance among energy, environment, and economy.

I work on three related programs: resource assessment in unconventional oil and gas reservoirs, subsurface micro- and nanosensors for enhanced recovery, and energy education. One of the opportunities now facing the world is developing the tremendous oil and gas resources found in shales. Toward this end, I co-lead, with Svetlana Ikonnikova and John Browning, a team of geoscientists, engineers, economists, and students working on a

Sloan Foundation-funded program to determine the capability of U.S. shale gas to contribute significantly to natural gas supply for the next 20 years. The team is studying four U.S. shale-gas basins, considering the resource base in place, production potential at various plateau levels, and implications for higher activity levels. Results of this research should help with informed regulatory decisions and thoughtful energy policy.

In terms of enhanced oil and gas recovery, much oil and gas are left behind in reservoirs. Imagine being able to put “smart dust” into small pore spaces, recover information, and even change reservoir conditions. To tackle this problem we formed the Advanced Energy Consortium (AEC), a multimillion-dollar annual program managed by a Bureau management team and directed by a Board of Management that I chair. The AEC’s mission is to develop intelligent subsurface micro- and nanosensors that can be injected into oil and gas reservoirs to characterize reservoir space in three dimensions and improve recovery of hydrocarbon resources. The AEC subcontracts 25 universities across the world. It is fundamental research at its core, with a crucial applied result.

Finally, I focus on energy and environmental education, including the reality of transitioning from fossil fuels to alternative energy. Together with director Harry Lynch, I co-produced and am featured in *Switch*, an acclaimed documentary on global energy. The film test-screened in 100 theaters nationally in early 2012 and had its major release in the fall, screening in 8 major U.S. cities and 60 universities. Funding from the O’Donnell Foundation will allow us to screen *Switch* at another 200 universities in spring of 2013, develop a video-based energy curriculum for primary education, and create treatments for a TV and/or web-based energy series.

The waltz of the 3 E’s—energy, environment, and economy—held together by education, represents the heart of the Bureau mission. The pages that follow hold countless examples of how the talented people that call the Bureau home make that mission a reality.

- 5 Advanced Energy Consortium
- 11 Applied Geodynamics Laboratory
- 18 Center for Energy Economics
- 22 Deep Shelf
- 24 Exploration Geophysics Laboratory
- 27 Fracture Research and Application Consortium
- 32 UT Geofluids
- 37 Mudrock Systems Research Laboratory
- 48 Quantitative Clastics Laboratory
- 52 Reservoir Characterization Research Laboratory
- 60 Shale Gas
- 63 State of Texas Advanced Resource Recovery
- 75 Texas Consortium for Computational Seismology



The Bureau gratefully acknowledges the following companies for software or dataset access: Halliburton (Landmark); Schlumberger; HIS; DrillingInfo; Austin GeoModeling, Inc.; CGG (Hampson-Russell); ParadigmSoftware, L.L.C.; Applied Imagery; Blue Marble Geographics; Midland Valley; GEDCO; Ikon Science; Badley Geoscience Ltd.; NORSAR; Dassault Systèmes; ION Geophysical; Computer Modeling Group Ltd.; and TerraSpark Geosciences.

More than 70 researchers work in the Energy Division at the Bureau. We concentrate on carefully selected areas of sedimentary geology that collectively contribute to assessment and development of energy resources. This “don’t try to do everything” approach allows us to bring significant human, laboratory, and computing resources to bear and has resulted in breakthroughs in several disciplines, such as salt tectonics, natural-fracture studies, reservoir characterization, and seismic imaging.

In addition to this thematic approach, we serve as part of the State Geological Survey of Texas, and we continue our record of Texas-specific geological studies in energy. Under our State-funded STARR program, this research includes in-depth work with oil and gas industry partners on exploration and development problems and regional studies that we pursue because they have potential as future oil or gas exploration plays. Recently STARR regional research studies have included Barnett, Eagle Ford, and Haynesville Shale plays; hybrid-lithology plays, including Wolfberry limestones and shales in the Permian Basin; and the Cleveland tight-sandstone play in the Panhandle. Other Bureau teams, such as natural-fracture, mudrock, and quantitative-clastics groups, are investigating these same plays. Why? Because so much remains to be learned about unconventional hydrocarbon systems.

Here is a brief guide to our major energy research programs and their acronyms:

AEC	Advanced Energy Consortium
AGL	Applied Geodynamics Laboratory
CEE	Center for Energy Economics
Deep Shelf	Deep Shelf Gas Reservoir Quality Project
EGL	Exploration Geophysics Lab
FRAC	Fracture Research and Application Consortium
UT GeoFluids	Geofluids Consortium
MSRL	Mudrock Systems Research Laboratory
QCL	Quantitative Clastics Laboratory
RCRL	Reservoir Characterization Research Laboratory
STARR	State of Texas Advanced Resource Recovery
TCCS	Texas Center for Computational Seismology

Over the last couple of years, we have reestablished our research program in geothermal energy in Texas because we are encouraged that more-efficient heat-exchange processes are now available, making more of Texas’ subsurface potentially prospective for geothermal resources. Geothermal is one of several areas in which we collaborate with our Bureau Environmental Division colleagues. Carbon storage, groundwater resources, and hydraulic-fracturing studies are other areas of routine collaboration between the two divisions.

—Eric Potter



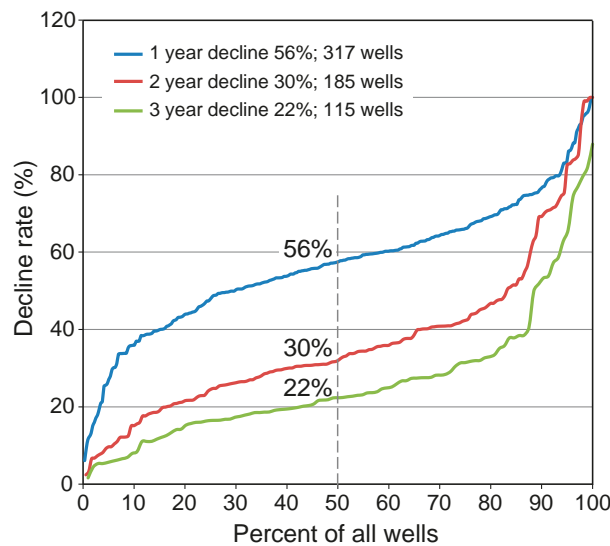
Drinking from the Fire Hose

Eric Potter

In my position as Program Director for Energy Research, I'm pleased to say that I find it impossible to keep up with the 70+ researchers in the Bureau's Energy Group. I suppose that I should know what they are planning, how their budget looks, what the sources of future funding will be, what their latest research findings are, who they would like to hire, and how long it will be until their next publication appears. I actually do work on these things, but fortunately most of the research teams are led by folks who are much better managers than I am and who excel at the tasks I just listed. They get all these tasks done, with only some gentle reminders from me and my assistant, longtime Bureau admin whiz, Jenny Turner.

Instead, I focus on providing help to these leaders in any way I can. I help make external connections that could result in new collaborations, access to datasets, or new funding. I try to learn enough about their research results to help connect them to other research, within and outside the Bureau, that I've learned about. I also use these research findings in talks that I give about the Bureau. I probably give the "BEG Overview" talk 20 times within any given year, and it's much more fun when it's full of new insights from Bureau research. In spreading the word about our research capabilities, I have to guard against becoming just a PR man. Smart people are doing great things everywhere.

To succeed, we need to complement the tidal wave of new knowledge with fossil-energy insight that is useful now or will lead to breakthroughs in the longer term.



JSG Area Annual Gas-Well Decline Rates, Barnett Shale.

Our research programs evolve quickly. The fast pace of doing relevant research while keeping ahead of competitors makes for interesting planning sessions. Forecasting research milestones is tough, like predicting the flight of a nighthawk. Get ready for unexpected, quick turns because they are necessary for survival!

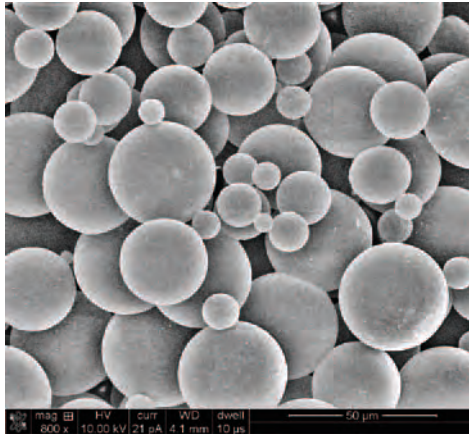
Aside from my administrative duties, I participate in two shale-resource research projects. As a service to the Jackson School (JSG), each year I estimate the future value of the JSG royalty interests beneath 177,000 acres in the western Fort Worth Basin of Texas. This acreage is all within the Barnett Shale Gas play, and some is within the best-performing part of the play. How good is the shale production in the JSG area? It's highly variable, but the average well will make a billion cubic feet of gas in its lifetime. How many shale wells will there be on the now partly developed JSG royalty lands? That's a more difficult question, but likely more than 1,500 Barnett wells, ultimately. I also participate in the Bureau's Sloan Foundation shale-gas study, which is engaged in forecasting the aggregate production from the top five U.S. shale-gas plays for the next 20 years.

Small Particles Provide Big Opportunities

Jay Kipper



The Advanced Energy Consortium (AEC) was developed as an extension of what was already happening in the medical industry. We asked ourselves, "If we can image the human body, why can't we extend the concept and image Earth's body?" The answer was "Let's give it a try!" And 3 years later, January 1, 2008, the AEC opened its doors.



The AEC is now one of the largest joint research consortia here at the Bureau. It is focused on the application of nanotechnology to the exploration and production of oil and gas. The goal of the research consortium is to develop subsurface nanosensors that can be injected into oil- and gas-well bores—smart dust. By virtue of their very small size, these sensors will be able to migrate out of the well bores and into pores of the surrounding rocks to collect data about the physical characteristics of hydrocarbon reservoirs. The data collected will enable the more efficient exploitation of hydrocarbon resources.

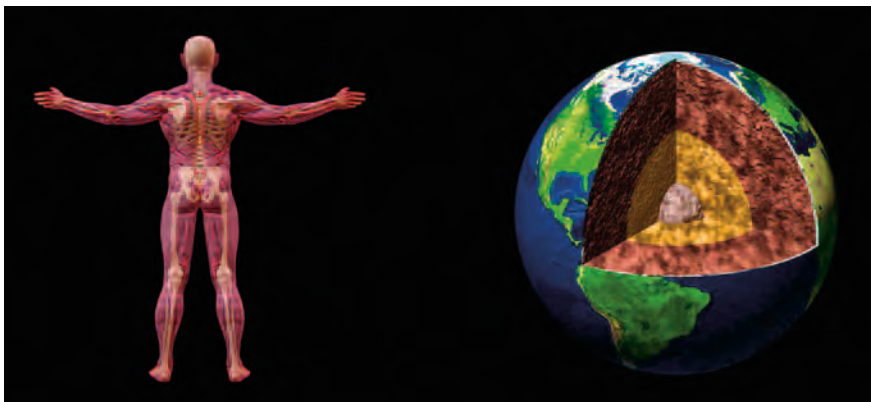
The AEC is a fascinating mix of innovation, technology, collaboration, and organizational structure. Rather than conducting all of the research here at the Bureau, the AEC has been able to engage the best and brightest minds from around the world through a competitive proposal and funding process. We fund more than 250 research professors, postdocs, and graduate students from 27

universities around the world. This type of research collaboration, coupled with our structured project management program, has created an explosion of innovation and technological development. Our consortium members have reported a huge leveraging of their financial investment in the AEC and are already integrating results from the AEC into multiple places in their organizations.

Who knows where the technology being developed at the AEC will lead us? But if we are able to better "illuminate" the reservoir, then we should be able to recover more hydrocarbons.

More hydrocarbons mean more resources to meet our ever-growing demand for energy—and that is a good thing!

The AEC is run by a group of talented people here at the Bureau, including Scott Tinker, Sean Murphy, David Chapman, Mohsen Ahmadian, Carla Thomas, Natalie Silva, Sharon Campos, and me.



Nanoparticle-Enhanced Reservoir Characterization



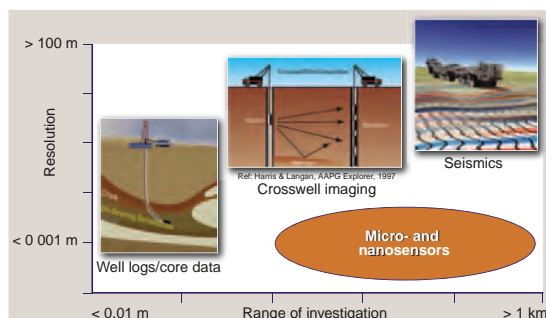
Mohsen Ahmadian

The Advanced Energy Consortium (AEC) comprises leading energy companies and global academic institutions facilitating precompetitive research in nanotechnology, with potential to enhance recovery of petroleum and gas from existing reservoirs. As a project manager for AEC, I am responsible for managing funding, implementation, administration, and reporting of awarded research studies. I manage two of four research thrusts at AEC—contrast agents and nanomaterial sensors (NMS)—representing 14 distinct projects at major academic institutions around the world with an annual budget of approximately \$4 million.

Contrast agents are molecules or nanoparticles having augmented electromagnetic, acoustic, or other properties that can be dispersed in fluids injected into an oil and gas reservoir, so as to increase a worker's ability to sense the spatial extent of these fluids by using available borehole, surface, and borehole-surface-imaging techniques. Leveraging available or existing tools has always been the consortium's approach—if these nanomaterial agents were to require new tooling and infrastructure, adoption would slow, and risk would increase.

Contrast agents are of particular interest to AEC members because of their potential to enable higher resolution, real-time imaging for delineating the location and path of fluids injected into oil and gas reservoirs. Applications could include waterfloods, hydraulically induced fractures, and CO₂ floods. Each of these applications has unique scales, chemistries, and operating conditions that require application-specific research and development.

The evolution of different contrast-agent approaches has been similar—AEC members first funded development projects to determine whether viable candidate nanomaterials existed that could be synthesized, were stable under reservoir conditions, and added contrast. Members have since funded modeling and simulation projects to verify that contrast is detectable under



a variety of applications, to identify parameters that might improve contrast (for example, size, distributions, volume), and to inform chemists screening and synthesizing contrast agents. At present three distinct contrast-agent approaches are being investigated—electromagnetic, acoustic, and dielectric. Plans are under way to demonstrate these contrast agents in the field within the next few years. AEC's NMS research thrust is aimed at developing nanoscale assemblies of molecules that perform a desired sensing function by exhibiting an irreversible and detectable state change when exposed to variations of physical or chemical conditions. The challenge of the NMS research thrust is to develop molecular-scale sensing, reporting, or payload-delivery mechanisms with adequate sensitivity and specificity to be effective in a harsh, heterogeneous, multiphase, chemically diverse environment. The possibility of combining large-scale reservoir simulations with ubiquitous monitoring from sensors embedded in reservoir fields could provide a new level of symbiotic feedback between measured data and model predictions, greatly improving tomorrow's production efficiencies. The major emphases of currently funded projects include (1) smart tracers, (2) reservoir reporters, and (3) hybrid solutions, which perform both reporter and enhanced oil recovery functions. Research that AEC and I are doing in these cutting-edge-technology areas has the possibility of revolutionizing the oil industry. And that is exciting.

Illuminating the Reservoir Using Micro- and Nanoscale Electronic Sensors

David Chapman



One challenge to improving oil and gas production is direct measurement of subsurface physical and chemical properties, more than several meters away from the borehole, in which fluids flow through submicron-sized pores in reservoir rock and fractures. A possible solution to this challenge employs anonymous, miniaturized, and injectable electronic sensors. The potential of miniaturized electronic devices is their ability to make multiple measurements of reservoir properties, along with measurement time stamping and geolocation metadata. The mission of the Advanced Energy Consortium (AEC) is to develop novel subsurface sensing technology, capable of directly measuring interwell physical and chemical reservoir properties, using nanoscale devices that enhance the commercial extraction of oil and natural gas via more accurate confinement of reservoir production models.

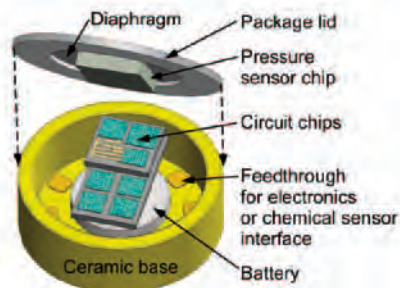
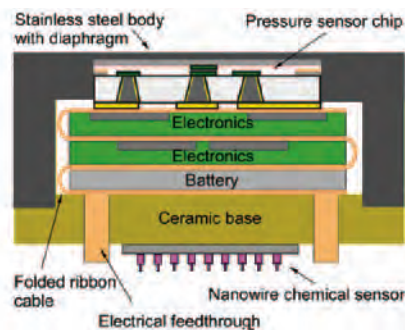
In 2012, the AEC's Microfabricated Sensors portfolio made significant advancements in sensor detection of analytes of interest, elevated-temperature survivability, and continued miniaturization of components, demonstrating needed capabilities in high-temperature power

sources and miniaturized wireless communications. Following the multiyear program plan, we have

down-selected sensor and power studies on the basis of successful proof-of-concept results. We have also successfully funded and launched a millimeter³-scale integrated sensor-system project, combining chemical, pressure, and temperature sensors so as to store time-stamped data to nonvolatile memory downhole.

As a Project Manager for the AEC, I lead the Microfabricated Sensors Research Thrust while chairing the AEC publications committee and managing invoicing for the \$38M consortium. The AEC researches development and application of subsurface nanosensors for oil and gas exploration and production. I manage multiyear, cross-university research projects for the AEC, drawing on proven strengths in technical and business development, with 15 years' experience in

advanced technology at Motorola, Intel, Research Triangle Institute, and SEMATECH.



Millimeter³-scale integrated prototype system being developed by the AEC, integrating time-stamped chemical, pressure, temperature metadata in a high-pressure, high-temperature-capable package in collaboration with researchers at the University of Michigan, Cal Tech, Rice, and Boston University. Multichip module (top) and ceramic packaging (bottom).

Photo courtesy of V. Gianchandani, University of Michigan.

Accelerating the Development of Advanced Nanotechnology in a University Environment



Sean Murphy

It wasn't just the desire to learn more about Earth processes, or to develop the skills to identify rocks and minerals, or even the realization that fieldwork (outdoors) and laboratory analysis (indoors) were equally important that crystallized my decision to become a geologist. Ironically it was an assignment by my undergraduate paleontology professor to read an essay by Thomas Chamberlain titled "*The Method of Multiple Working Hypotheses*" (1897, *J. Geology*, 5, 837-848) that sealed my vocation. Wow! Here was a field of science that anticipated the human urge to jump to conclusions and developed a methodology acknowledging that the most obvious or intuitive explanation for observed phenomena might not be correct.

Now, 30 years later, I am working in another field of science that turns conventional thinking on its head and provides a template for the multiple-working-hypothesis approach—nanotechnology! When materials are shrunk to the nanoscale, the surface:volume ratio is so high that they tend to be more reactive than their bulk equivalents with unanticipated kinetics. Other basic properties are also unexpected and unpredictable; for example,

the color of the metal gold is red at 2 nm, and these particles melt at a temperature lower than that of bulk gold (<600°C vs. 1060°C).

I am currently blessed to be Program Manager of a Bureau-led consortium—AEC—which has as its aim nurturing research in this nascent field and directing it toward nano-based tools and sensors to enable increased hydrocarbon recovery from existing fields. The petroleum industry typically leaves 50 to 70 percent of hydrocarbons unrecovered because no one can locate the bypassed zones or access the residual, or they leave it trapped in tight, microscopic pore spaces in the rocks. Fortunately, nanoscale materials are small enough (1 billionth of a meter) that they can penetrate these small spaces.

When AEC was first founded, it wasn't clear that useful applications would result from funding basic research in the nanosciences. But 5 years later, AEC has demonstrated its value to the industry by expertly coordinating research from 30+ different institutions worldwide by organizing a broad research portfolio into technical thrust areas to enable new micro- and nanosensing technologies and by providing funding for hundreds of professors and students. Systematic project management and thoughtful integration of the diverse research portfolio by Bureau scientists have shortened the research development timeline, and a number of promising applications will soon be demonstrated in the field. Planning is under way for large-scale demonstrations that use nanomaterial contrast agents to provide real-time imaging of enhanced oil recovery flood fronts and determine the extent of hydraulically induced fractures. The organizational methods, integration strategies, and frequent communication coordinated by the Bureau/AEC team of project managers are enabling talented researchers to develop incredible new technologies for the oil and gas industry.



Photo courtesy of Brian Royvill

Scouting possible field-demonstration sites, where nanomaterial-based contrast agents can be used to provide real-time imaging of injected fluid flow paths. RMOTC, Teapot Dome oil field near Casper, Wyoming.

The Magic of Making Particles Move through a “Solid” Object

Carla Thomas

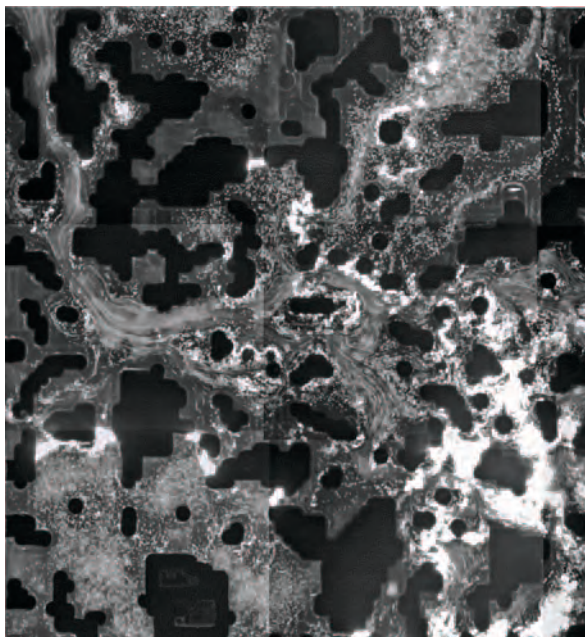


How do you get particles to move through a supposedly solid object? That is the question we are struggling with in the Advanced Energy Consortium (AEC) as we think about deploying nanoscale sensors to aid advanced oil and gas recovery. But the answer is not just to make the particles small, very small. In fact, we already know quite a bit about what not to do to get these sensors, or particles, to move through rock, which is primarily to ignore the chemical and electrostatic nature of the rock pore walls, the brine or oil mixture contained there, and the nanoparticle surface itself. Instead, through the support and technical oversight of the eight companies representing the AEC, we have compiled a portfolio of research projects dedicated to our understanding of nanoparticle movement through the reservoir, focusing down to the molecular scale.

Logistically we spend many hours in web-based conferences but meet face to face a few times a year to review our work and brainstorm in targeted workshops. Our goals are twofold: (1) to engineer coatings for these nanoparticles that would satisfy the need to both maximize nanoparticle stability

and minimize nanoparticle retention for specific downhole applications and (2) to generate a validated simulation strategy for predicting particle transport through reservoir systems. Our methods include all the computational and experimental tools available commercially or developed in-house by the various researchers under contract. Our methods cut across many scales, from quantum physics calculations paired with atomic force microscopy measurements to reservoir-scaled mass-transport prediction coupled with standard core-flood testing. In our third year of research, we have challenged ourselves to move experiments toward ever more typical ranges of reservoir conditions, with an

emphasis on including chemical adsorption and desorption compensation in their pore-scale flow simulation and simultaneously testing nanoparticle suspension stability at high salt concentration and high temperatures. For our fourth year of research, we hope to introduce multiple phases and components into our pore-scale micromodels and core-scale flood experiments while beginning study of and compensation for clays in our adsorption experiments and coating designs.



High-speed camera images of white fluorescing nanoparticles in 2.5D micromodel showing areas of particle retention, low penetration, and preferential flow.

Photo courtesy of Dimitris Nikitopoulos, LSU

Supporting the Advanced Energy Consortium



Natalie Silva

Over 4 years ago, I began playing a supportive role as program coordinator for the AEC, a group pursuing a new, undefined aspect of research: bridging nanotechnology in oil and gas reservoirs to improve recovery of hydrocarbon resources. Our journey has taken us around the globe to seek out the best researchers and inform them of our consortium's needs. In our search, we have hosted an array of meetings and workshops to provide information regarding the mission of the AEC. And, as our program has matured, we continue to host myriad meetings and teleconferences to foster communication between members and researchers.

One of my responsibilities is to ensure that all meetings are planned, organized, and executed accordingly. If it sounds like fun, it is! I have enjoyed the tasks of securing suitable venues for our events, organizing the catering, working diligently with university administrators to acquire all necessary approvals, and, finally, welcoming our guests to the event. I even appreciate the frantic moments resulting from an unfortunate surprise. When



Photo courtesy of Brian Roswell

coordinating events, I have found that Murphy's Law always applies! However, I must say that, hands down, the best aspect of my job is being able to learn from our researchers, staff, special invited speakers, member companies, and directorship. I have come to see how fortunate I am to work with some of the brightest minds on this planet.

Another part of my role is assisting the Bureau's Contracts and Grants Department when new AEC projects are awarded, current projects renewed, and when new members are added. Each party is under a formal obligation, and an understanding of the agreements is essential to the business aspect of the AEC.

When I first started my career at the Bureau, I knew I wanted to make a difference but was unsure how. I now know that, by supporting the AEC, I work as a valued team member accomplishing objectives that affect each and every one of us. In the AEC program, we are on the cusp of realizing leading technological applications—that is, making what was once just an idea on paper come to life. What an exciting time to be here at the Bureau!

Salt Tectonics

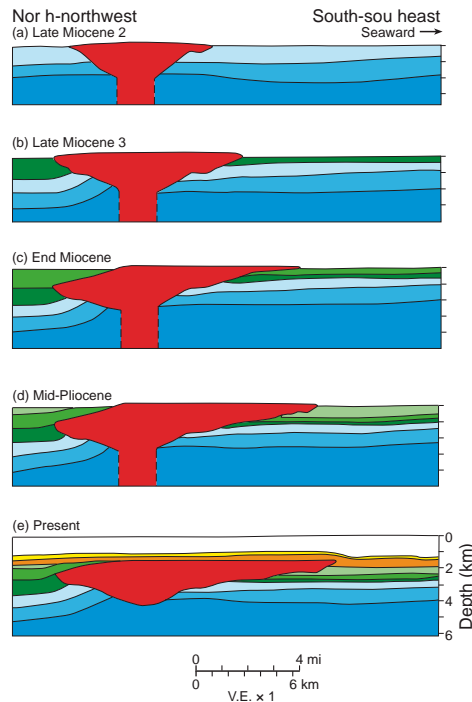
Dr. Michael Hudec



Many of the world's great hydrocarbon provinces—the Persian Gulf, Zagros foldbelt, North Sea, offshore West Africa, offshore Brazil, Gulf of Mexico—are salt basins. Geologists working in these basins have to have an understanding of salt tectonics because salt and salt structures can influence every aspect of a hydrocarbon system, from source-rock distribution to trap and seal. This task is made more complex because salt structures degrade the quality of seismic images, adding noise to data just in the areas where clarity is most needed.

The job of the Applied Geodynamics Laboratory (AGL) consortium is to help geoscientists in our member companies improve their interpretations around salt structures, not by improving the quality of seismic data, but, rather, by providing interpretation guidelines and conceptual models for the evolution of salt structures. Geologists and geophysicists can better interpret fragmentary seismic data around salt structures if they have some concept of what the structures are supposed to look like.

At AGL, we develop these concepts by combining structural analysis, physical modeling, and numerical modeling. These AGL branches are complementary: structural analysis examines types of salt structures that exist in nature and provides insights into their evolution through structural restoration; physical modeling confirms, modifies, or in some cases rejects models proposed in structural analysis; and numerical modeling provides an understanding of the physics that drives salt structures to evolve the



Geologic model for emplacement of a salt sheet, deep-water Gulf of Mexico.

way they do. When all three legs of this tripod work together, resulting models are physically reasonable, consistent with model simulations, and based on real structures observed in nature.

As co-Principal Investigator of the AGL, I help direct research and ensure that all three branches of research work together to produce the best results. I am a structural geologist, so my personal research focuses on structural analysis of salt basins. This analysis occurs at two scales. First, I am interested in how certain types of salt structures evolve. For instance, my recent studies have explored how minibasins subside or how salt sheets and canopies

advance. At a larger scale, I am also interested in the evolution of entire salt basins, looking for examples of how seafloor spreading affects the evolution of salt basins perched on either side of the ocean. Recent basin-scale studies have included analysis of the Kwanza Basin (West Africa) and the Gulf of Mexico salt basin.

At present, co-Principal Investigator Martin Jackson and I are writing a textbook on salt tectonics. Slated for completion in 2014, this textbook will include a mix of salt-tectonic theory and practical application to hydrocarbon exploration. Much of the textbook will be based on results of 2 decades of AGL research, although large parts are also based on work of many other researchers in the field, some of whom have delved into topics never touched by AGL. I like the chance to stretch myself on new topics in salt tectonics, and I look forward to new revelations in the coming years!



Terra Infirma

Dr. Martin P. A. Jackson

Like glacial ice, rock salt (a source of table salt) is a solid we can walk on or mine in caverns, but over geologic time, it flows. Rock salt and other minerals formed by evaporation are the fastest flowing crystalline rocks in the shallow crust—truly terra infirma. This fluidity has created astounding structures. Underground mountain ranges of salt are hundreds of kilometers long and taller than the greatest mountains on Earth. Salt glaciers spreading over the landscape, and even the seafloor, can merge like coalescing pancakes to form salt canopies the size of entire countries. Salts on Mars may help to explain the origin of the longest, straightest canyons in the solar system!

But what's the special property of rock salt that allows it to flow so easily? What forces set it in motion? What is the internal structure of salt bodies? How does salt flow affect other rocks nearby? These are the salt-tectonic questions we try to answer. With Mike Hudec, I lead research at the Bureau's Applied Geodynamics Laboratory (AGL) by examining naturally formed salt structures in several ways. Examples of salt tectonics are typically deeply buried and offshore, and we study them using seismic data produced by the oil industry. These salt structures are buried under many kilometers of sedimentary rocks and typically offshore. Not all salt bodies are so inaccessible, however. Mountain building and erosion have exhumed many salt bodies worldwide. We can map these outcrops in great detail on foot and using satellite images and aerial photographs. Surveys of natural salt-tectonic structures suggest answers to the scientific questions posed earlier. We test these ideas by physical models in the laboratory (Tim Dooley) and by constitutive models (Maria Nikolinakou) and numerical models (Gang Luo) on computers. We then interpret these modeling results using principles of structural geology, rock mechanics, scaling theory, and Newtonian physics. This analysis produces new ideas that

we add to our conceptual toolbox and reapply them to nature to test their soundness.

These questions are pure science, but they also have great practical implications. Since 1988, the unique AGL program has attracted \$16 million in research funds. Almost all funds are from oil companies and seismic companies. Buried salt basins in the deep-water margins or mountain belts of several continents have yielded major discoveries of oil and gas, and an understanding of salt tectonics is a key to this exploration. Salt flow creates structures in the nearby sediments that can trap oil or gas. Salt flow also influences the pattern and type of sediments that form hydrocarbon reservoirs. Salt bodies distort the passage of seismic waves. To predict the depth and position of a deep exploration target accurately, geophysicists must produce an accurate map of the three-dimensional shapes of overlying salt bodies distorting the seismic waves. This mapping often entails interpreting shapes of salt bodies from shadowy images, so it is most reliable if guided by principles of salt tectonics. Our goal is to continually improve understanding of these principles.



Testing new field equipment under the skyline of Kuh-e-Namak (Iran), the most spectacular mountain of salt on Earth.

Photo courtesy of Jean Leuzouery

Sandbox Models: Visualizing Salt-Related Deformation

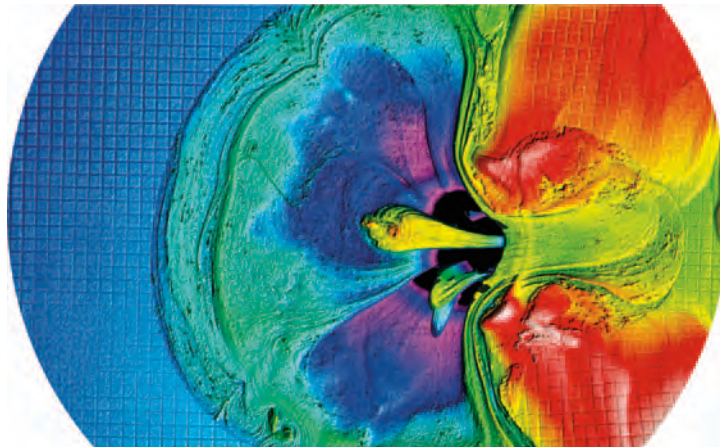
Dr. Tim Dooley



Deep-water salt basins such as the Gulf of Mexico, the North Sea, and offshore Brazil are targets of intense oil and gas exploration. Deformation of hydrocarbon-bearing sediments above, below, and adjacent to salt bodies is an incredibly complex

process that occurs over millions of years, for although rock salt appears solid, over geologic time, it actually flows. How can we visualize these processes in order to understand the evolution of the salt bodies, as well as deformation of the encasing sediments? For the past 24 years I have been building physical tectonic models to do just that. Since 2003 I have run the tectonic modeling laboratories at the Bureau, which are part of the Applied Geodynamics Laboratory (AGL), an industry-funded consortium dedicated to the study of salt tectonics. (See Martin Jackson's page for details on the AGL and for more information on salt tectonics.)

These physical models are run in what can be described as tabletop sandboxes. The sandpack is composed of stacked layers of different-colored sands representing sedimentary strata. Buried within this sandpack is silica gel that is an analog for rock salt. Each experiment is designed to simulate on a small scale the type of geologic system we wish to model. For example, the bottom of the sandbox can be split to mimic fault motions, or it can be tilted to mimic gravity-driven salt tectonics as seen in the Gulf of Mexico and offshore West Africa. In other models, sidewalls of the box can be moved in and out to simulate tectonic compression or extension. During deformation



the silica gel behaves in a fashion different from that of the brittle sediments. For example, during compression the gel is weaker than surrounding sediments and focuses deformation.

Cylindrical bodies

of "salt" (diapirs) can

rise up through the sediments, breach their roof, and form surface extrusions of "salt" (see image). This type of feature is seen in the Zagros Mountains of Iran. In gravity-driven systems, the thickening sedimentary pile can drive the gel upward to eventually overlie sediments that are younger than the salt body itself. The great Sigsbee salt nappe in the Gulf of Mexico formed by the coalescence of numerous salt sheets, which grew from a source layer of salt buried miles below the surface.

As the models evolve over days, or weeks, they are constantly monitored by an array of high-tech computer-controlled equipment. Digital cameras take photographs from above and below every few minutes and track the motion of every particle. After the experiment, these images are combined to form a time-lapse animation, showing how the experiment evolved. A laser scanner monitors the surface topography with 0.5-millimeter accuracy. When the experiment is complete, the model is soaked in gelatin, left overnight, then sliced like a loaf of bread into 200+ closely spaced sections. Photographs of these sections are combined to create a 3D virtual model. We can "fly through" the model on a computer, much like a CT scan, and examine the complex internal structure of the model.



Modeling Salt Basins

Dr. Gang Luo

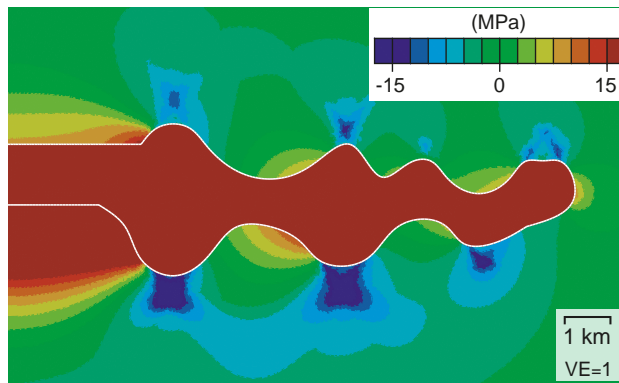
In sedimentary basins, salt bodies are closely related to oil and gas reservoirs, but many mechanical properties of salt bodies are different from those of surrounding sediments. In particular, salt mechanical properties suggest that salt bodies behave like a solid for short timescales (<3 months) and like a fluid for longer timescales (>10,000 years). Hence, studies of a system consisting of salt bodies and surrounding sediments (salt-basin system) and mechanical interactions between them have become increasingly more important for scientific insights, drilling issues, subsurface seismic imaging, and exploration of oil and gas reservoirs. Major questions include why borehole instability often happens during drilling through or near salt bodies and why some anomalies of physical properties and mechanical parameters (for example, stresses and fluid pressures) usually occur near salt bodies. Also, how do different geometries of salt bodies (for example, salt sheets and salt domes) develop during long-term geological periods? And how do these different geometries of salt bodies have an impact on borehole stability and drilling designs?

Finding direct answers to these questions is difficult, and understanding and predicting mechanical interactions between salt bodies and surrounding sediments in salt basins have been a challenge for geoscientists. One helpful possibility

is a tool in which numerical modeling (computer modeling) might be used for simulating these processes, exploring basic physics, and predicting major mechanical parameters (for example, stresses and fluid pressures). However, building numerical models to simulate this salt-basin system is an even bigger challenge for geoscientists because of the lack of professional software for dealing with these issues, numerical calculation errors, insufficient

computational capacity, and so on. My mission here at the Bureau is to develop numerical models so as to investigate the motion and evolution of salt bodies; the mechanics, feedback, and interactions between salt bodies and sediments in salt basins; and borehole stability near salt bodies. It is my lifetime goal, in fact, to make the *possible* tool become an *efficient, important, and powerful* tool.

I am a Research Associate at the Bureau, working in the Applied Geodynamics Lab (AGL) and GeoFluids groups. My research focuses on geomechanical modeling of salt tectonics, fluid flow, pore pressure, and well-bore stability, as well as finite-element modeling of fault interactions, stress triggering of earthquakes, lithospheric stress and strain evolution during earthquake cycles, and crustal/lithospheric geodynamic processes.



Perturbations of minimum principal stress near salt bodies relative to far-field values. Model results are consistent with observations of gradient drop in minimum principal stresses below salt and lost circulation above salt.

Drillers Stress Out with Relaxing Salts

Dr. Maria A. Nikolinakou



I employ geomechanical models that couple stresses and pore pressures so as to improve borehole stability calculations in complex geologic environments, such as around salt or close to dipping structures.

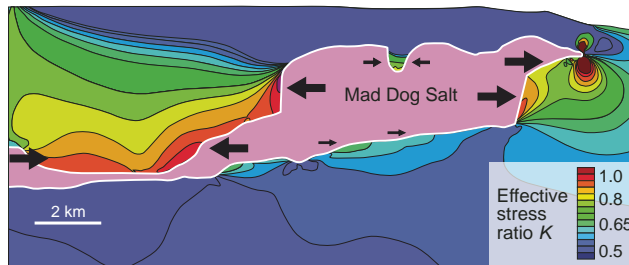
When designing a borehole, we need to ensure that fluids inside the well will balance against pressures from the Earth to prevent collapse of the borehole

and a violent escape of fluids. We cannot be too conservative, however, because high mud pressures in the well can fracture the surrounding formations and lead to the loss of circulation. Two values are critical to borehole stability: pore pressure and minimum principal stress of the formation. In an undisturbed sedimentary basin, these values are relatively straightforward to predict. In contrast, pressure anomalies are often encountered near and below salt bodies, resulting in numerous borehole failures.

Salt, which appears as a solid rock formation in the subsurface, is present throughout the world. The main mechanical characteristic of salt is that because it cannot sustain any differential loading, it deforms (relaxes) so as to achieve an isostatic state. As salt is buried among other sediments, this relaxation process loads the neighboring formations, resulting in elevated pressures and stress levels around the salt that are different from the general stress state of the basin. More than 70 percent of deep-water oil reserves worldwide are found below salt bodies; therefore, salt must be drilled through so that the hydrocarbon reservoirs can be reached.

Consequently, an understanding of the stresses and pore pressures around salt bodies is critical to the design of safe drilling operations.

Previously published results show that simple models have been unable to capture the complexity of salt-sediment interaction. At the Bureau, we use coupled models developed specifically for earth materials to simulate how stresses evolve around salt.



Numerical analysis of a Gulf of Mexico salt body (Mad Dog), illustrating that salt is pushing outward onto the sediments, elevating horizontal stresses within minibasins and in front of the salt.

Our key results, summarized in the *AAPG Bulletin* (v. 96, no. 1, 2012) are: (1) salt affects stresses in sediments miles away from the salt body, (2) the shape and extent of the salt play a key role in the dominant direction of stress/pressure changes, and (3) because pore pressures due to salt relaxation require millions of years to dissipate, they may still be present today.

Another example of the importance of coupled geomechanical analyses is trap integrity (how much oil or gas a reservoir can hold). Reservoirs often span hundreds of feet in elevation, establishing a preferred flow path, and this fluid flow changes the stresses at the crest of the reservoir. Typical noncoupled industry workflows often conclude that the caprock must be fractured and leaking; hence, drilling of the reservoir has no value. However, a simple coupled analysis reveals a different pattern of stress changes in both vertical and horizontal directions and shows that either the horizontal or the vertical stress, or both, can be greater than the overburden. As we discuss in our 2012 ARMA publication, these results offer greater confidence in the trap integrity of inclined reservoirs.



Tracking Plates

Dr. Ian Norton

Tectonic plates wander the planet over time scales of millions of years, marking their journeys with ever-changing mountain ranges, ocean basins, and volcanoes. My research tracks the motions of the plates, with a particular focus on the extensional basins that separating plates leave behind. One of these basins is Death Valley in California. This valley was formed very recently, only in the last 3 million years, and it is a result of plate interactions between the Pacific and North American plates.

With wonderful outcrop and a fascinating story to tell, this area is one of my primary research playgrounds. Another area of interest to me is the Gulf of Mexico. It is surprising how little we know about details of how the Gulf formed between 200 and 150 million years ago, given the huge volume of data and the Gulf's obvious economic importance. Together with other U.T. researchers, I focus on collection and interpretation of data specific to this problem.



A Picture Is Worth 1,000 Words

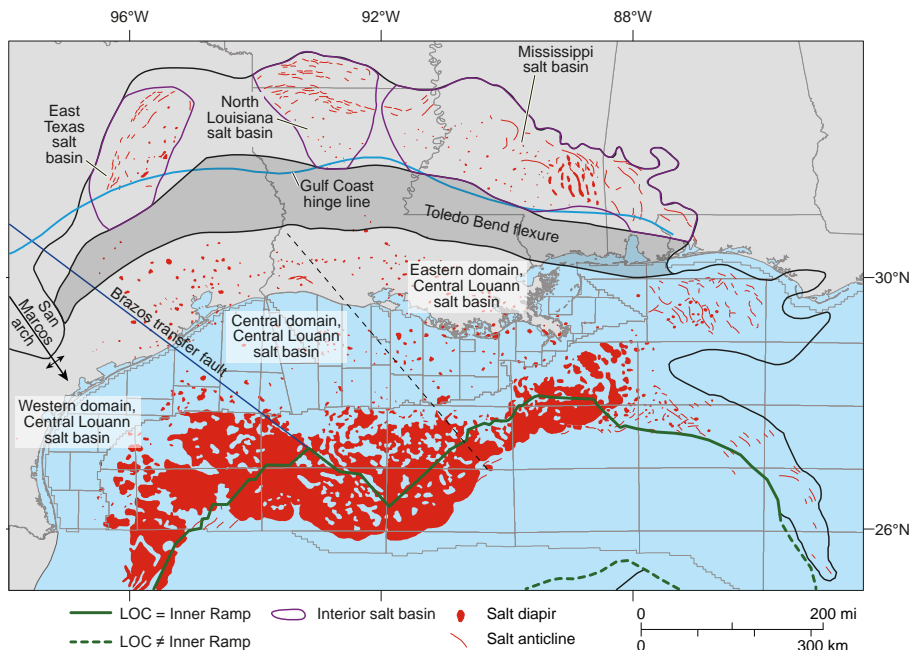
Nancy Cottington



I'm a computer illustrator for the Applied Geodynamics Laboratory (AGL) industrial consortium, producing geologic illustrations for publications and conferences. An illustration can

logos and advertisements. Within the scientific community, this branding translates into maps and other visual aids, with layers upon layers of information crowded into a small area trying to

represent complex ideas. When a scientist is publishing in the arena of globally and historically significant research, professionally made figures are worth the cost for his or her target audience to be reached in the most clear and concise manner possible. Dedicated drawing programs are becoming more and more complex in the industry, and it is not an efficient use of a Senior Researcher's time to spend hours navigating the program's labyrinthine processes. That's where I come in. I help the



take the place of reams of text by conveying an idea or showing an example. Within the limited space available for publishing in a journal or book, an illustration can be an effective use of that space. I have included an example of my work herein.

Companies across the globe spend billions of dollars on advertising and branding annually to make sure that their identity, message, and purpose are communicated through their

AGL researchers make the most efficient use of their time by supplying them with the professional illustrations they require when they need them!

In addition to illustrating, I also assist in organizing a yearly meeting of 300+ people for the AGL consortium. I manage the group's database of contacts and assist in communicating with its members.



Saving the World from Itself (Maybe)

Dr. Michelle Michot Foss

Businesses do it. Governments do it. All consumers, customers, and suppliers do it. Every day “billions and billions” of decisions get made about how energy products and services are found, developed, bought, sold, moved around, processed and converted, and used. How do people think about these decisions? Why do we make the decisions we do? For that matter, how do we evaluate information about anything, perceive risk and uncertainty, discern benefits and costs, and make decisions? Turns out that this is a pretty messy business.

The role of a practicing economist often is pointing out why some things can’t be done the way people prefer, if they can be done at all, and what the alternatives might be. Not many people like to hear caveats, exceptions, problems, or challenges. Franklin Roosevelt famously quipped that he wanted a “one-handed economist.” During times of stress, like major recessions, commodity price peaks (or collapses), other defining events, or even just general living—buying a home or car, disciplining a child, trying to invest well for nest eggs—a common desire is for clarity. Fuzziness is not something we’re comfortable with (unless we are politicians). On top of that, we truly are, as David Brooks put it, “social animals.” Our thought processes and decision-making are plagued by the vagaries of emotion. We act in accordance with mental biases and maps that we don’t even realize are forming. The difficulty of trying to comprehend human behavior and how we make choices is enough to make one want to be a rock jock! Economic thought encompasses defining



Photo courtesy of NASA

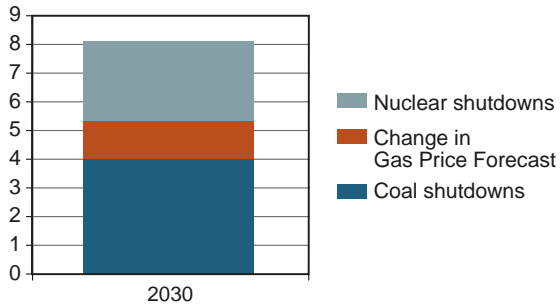
critical assumptions and demonstrating various outcomes that can arise if even slight changes occur to those assumptions—which means creating fuzziness rather than clarity—and yet revealing alternatives is exactly the power of economic analysis. We, the practicing economists, search for signals in the noise of information overload in societies that are, ironically, data starved; we never have the information that we really need. Thankfully, human behavior is

not a total mystery. We have some well-defined patterns and quirks, and economists are coming to understand how our foibles affect market outcomes.

Leading an energy economics research group within an organization like the Bureau, and being based at a university, I can be, and should be, pretty wide ranging and independent when it comes to research problems. As Program Manager and Chief Economist at the Bureau’s Center for Energy Economics (CEE), my job, my driving force, is to ensure that we tackle the most interesting and relevant questions and problems that we can handle. It’s true—we are obsessed with cost and whether decision-makers of all stripes really discern costs properly. Costs are too often misrepresented in matters of enormous policy debate and consequence. Businesses make potentially terrible decisions if they are not honest about costs, and potentially intelligent ones if they are. Bottom line—my job is to make sure we have lots of other, well-thought-out “other hands” in a complex energy world.

A “Dismal Scientist” at the Bureau

Dr. Gürcan Gülen



Additional natural gas use for power generation.

As one of the few Bureau “dismal scientists,” I sometimes introduce myself at meetings as the E in BEG. I like to think that economic analysis renders geologic research implications easier for an audience to digest, especially energy-policy makers. Energy economics and geology seem to overlap because our economy will continue to depend on hydrocarbons for some time to come. The supply of reliable, affordable energy having minimal negative environmental impacts is crucial to the growth of a healthy economy. Often, however, objectives and forces compete, pulling the energy-policy debate and the industry in different directions. Renewable portfolio standards; tax credits for renewables; environmental regulations on land, water, air, or climate at the State or Federal level; regulations on land access; oil- and gas-taxation policies; import-export tariffs; technological advances; and trends in capital markets are just some of the factors that impact the direction the energy sector may take. Although many may desire a “one-handed economist,” in such a complex environment even two hands are insufficient to cover plausible alternatives. Maybe an ambidextrous economist would be best!

Recently I have been focusing on natural gas–power linkages. Using AURORAxmp, a powerful

economic dispatch model, my research group at the CEE has evaluated the impact of proposed EPA regulations on SO_2 , NO_x , mercury, and other hazardous air pollutants; a possible tax on GHG emissions; and an alternative, cyclical natural gas price scenario on demand for gas in the power sector. We have also assessed the impact of adding new transmission lines in west Texas, so as to allow wind farms to send more power to the grid. Somewhat surprisingly, they do relieve congestion but do not induce additional wind capacity beyond that induced by tax credits or new regulations on emissions.

More recently we filed an analysis of a proposed increase in the energy price cap with the Public Utility Commission of Texas. Our new energy analyst, Michael Soni, has been leading the modeling for this project. Texas has a competitive electricity market, and new generation is built primarily by merchant companies in response to price signals. Many are concerned, especially after the record-breaking summer of 2011, that peak demand might grow too fast and that price signals are too low for new power plants to be built. Our analysis shows that raising the price cap will enhance the price signal, increase reserve margin, and reduce involuntary demand curtailment.

We have taken an additional step in evaluating the impacts of results from these analyses on Texas’ economy. For example, changes in electricity prices and investment in new generation capacity will influence employment, revenues, and output. We use REMI PI+, a tool also used by the Texas Comptroller of Public Accounts, to estimate these economic impacts. We are also evaluating the economic impacts of CO_2 -EOR investments. Next in line are midstream and downstream investments to take advantage of increased liquids production in the state. Doesn’t it sound like we are having fun?



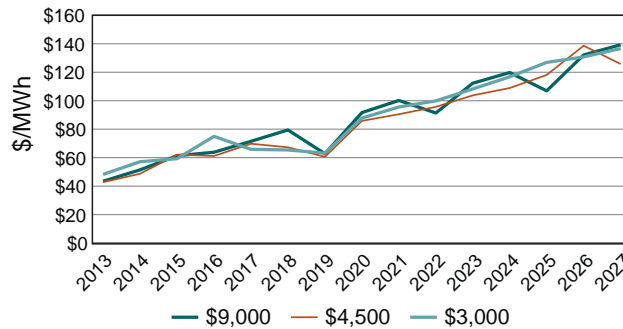
Power Economics in Texas

Michael Soni

As a newly established energy economist at the Center for Energy Economics (CEE), I focus on evaluating the effects of policy changes, commodity prices, and renewable energy incentives on electric grids, with a strong focus on the ERCOT market. Most of my

research relates to the current resource adequacy debate. Within a larger study of power economics at CEE, I have become heavily involved in the modeling aspect of our research. Thus, I have become an extensive user of powerful economic dispatch software, AURORA_{xmp}, in which the decision to dispatch electric generators is based on a variety of factors, including demand growth, energy efficiency improvement fuel prices, and capital expenditure rates for new generators in both the short term and the long term. The long-term optimization logic determines when economic investments are necessary by comparing the real levelized net present value of potential and existing units. Essentially the model determines which generators should enter or from retire the electric grid according to the profitability of each unit. These forecasts also provide information about how investment decisions are made in the electricity market. Running the model is the easy part; the challenge comes in determining the accuracy of ERCOT generator data by examining the objectiveness of input data and the feasibility of the output results.

My research with the CEE extends beyond modeling and simulations, however. As an energy economist, I frequently attend seminars and



Average wholesale price of electricity under different energy, price caps (nominal).

conferences to keep in touch with industry professionals and to obtain a hands-on feel for the energy market from industry participants themselves. I have attended several hearings held by the Public Utilities Commission of Texas concerning resource adequacy

in the electric grid that helped to increase my understanding of the power market tremendously and achieve my research objectives. Since joining the Bureau in May, I have become a well-rounded power economist. I genuinely enjoy studying the economics of the electricity sector because of its daily application and dynamics. In the future, I would like to expand my knowledge of energy economics into other areas of the power sector, such as resource economics. I think that my current research and exposure have helped give me a glimpse into the complexity of efficient allocation of our planet's natural resources. I specifically wish to increase my understanding of the economics of the natural gas value chain, including the drilling, storage, and transportation of this valuable commodity. More generally, I would like to begin to explore environmental economics by focusing primarily on the economic effects of taxes, tariffs, and environmental regulations. I would also like to look at the relationship between public policy and energy-infrastructure development in the United States. Overall, my long-term goal is to become knowledgeable in many different aspects of the energy industry, from drilling to power, for a more cohesive analysis of the energy industry as a whole.

Oil and Gas Producer Economics

Miranda Ferrell Wainberg

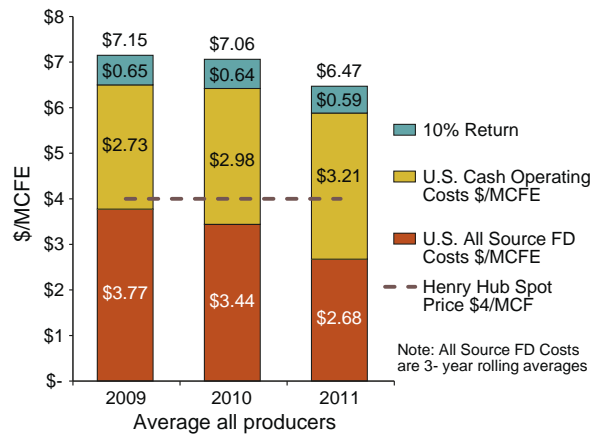


The reliable supply of oil and natural gas at affordable and predictable prices is a key input of economic activity and quality of life. Of the many factors influencing oil and natural gas prices, producer costs are the first determining factors underlying current and expected prices. As a result, in 2011, my group and I at the Center

for Energy Economics (CEE) began to track costs for a sample of 16 companies that represented almost 60 percent of U.S. total marketed natural gas production. We calculate a full-cycle producer cost that includes finding and development (F&D) costs, cash operating costs, and an assumed return on investment (ROI) of 10 percent. These are all essential costs incurred by an exploration and production company as it goes about its business of finding oil and gas. In 2012 we extended this analysis to cover the upstream (exploration and production) operations of a group of 11 national oil companies (NOC's).

With respect to U.S. natural gas producers, only 2 of our sample of 16 producers demonstrate upstream cost structures that fall below a widely discussed target Henry Hub price of \$4 per thousand cubic feet (Mcf). These results suggest that, on average, a Henry Hub price of \$6/Mcf is necessary for our sample of gas producers to remain financially healthy, indicating an upward pressure on U.S. natural prices.

The full-cycle producer cost for our national oil company sample includes another element,



in addition to F&D costs, which is cash operating costs and a 10 percent ROI: the fiscal contribution (FC) to the State. The FC to the State includes price subsidies for fuel products, dividends paid to government shareholders, and cash expenses for the country's social and economic development. We expect this component

of the full-cycle cost to be relatively inelastic, given the revenue dependency of many of these governments on their hydrocarbon sectors. The full-cycle NOC sample cost in 2011 was \$69.07/barrel of oil equivalent (boe). When 2011 capital expenditures were substituted for the 10 percent ROI, the full-cycle cost increased to \$80.09/boe. This result is consistent with that of other research, which calculates a full-cycle cost of \$90 to \$110/barrel for OPEC members. Our NOC sample and OPEC accounted for 56 percent of total world crude-oil production in 2011, with a weighted full-cycle cost of \$83 to \$100/Boe. This result implies that prolonged oil prices at the bottom of or below this range could be financially damaging for national oil companies and their countries.

As a Senior Energy Researcher at the CEE, I conduct research in natural gas and liquefied natural gas (LNG) value chains, national oil companies' performance and commercial frameworks, and Latin American energy issues. I also lecture on these topics in various CEE training programs and participate as an expert discussant in industry conferences on these matters.



From Sand to Sandstone

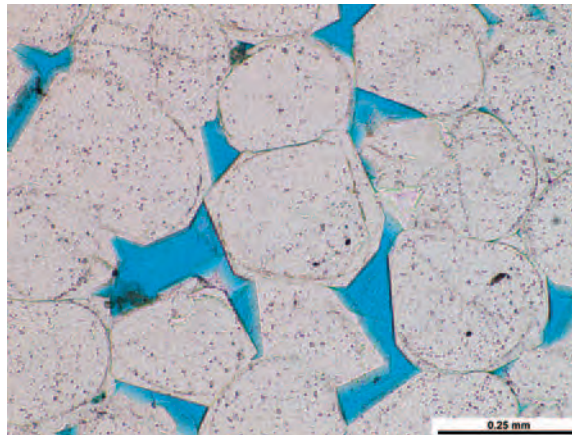
Dr. Shirley P. Dutton

I study pore space in sandstones, particularly sandstones that contain oil or natural gas. My specialty is studying the processes that reduce porosity in sandstones from the time they are deposited through their burial to increasingly greater depths and higher temperatures. The extent of porosity loss during this process is an important factor in determining the ability of the sandstone to hold and flow hydrocarbons.

When sand is deposited in an environment such as a river, beach, or delta, it contains pores, or empty space, between the sand grains. It is similar to a pail full of marbles, except that the sand grains are about 100 times smaller than marbles. Just as a pail of marbles can hold a lot of water, newly deposited sand contains water in the pores between the grains. Approximately 40 percent of the volume of the sand deposit is pore space filled with water.

As more and more sand and mud are deposited on top of it, the original sand bed is buried to greater depths and higher temperatures, and it undergoes chemical and physical changes (diagenesis) that convert it to sandstone. Some of the sand grains are ductile and deform as the sand is buried, causing some pore space to be lost by compaction. (Think of a bucket of marbles interspersed with peas being compacted by a heavy weight.) As the sand is buried, minerals can precipitate from the fluids in the rock into the pore space, and these

minerals (called cement) reduce the amount of porosity and also make it more difficult for fluids to flow in the rock. Some of the original sand grains may dissolve and form new pores. The sandstones become hydrocarbon reservoirs if oil or gas migrates into the sandstones and are trapped in the pores. The processes of diagenesis are not uniform, so it is important to understand how diagenesis and, therefore, reservoir quality varies spatially.



For the past several years, my research has focused on very deep, hot sandstone reservoirs in the Gulf of Mexico. Exploration companies are drilling wells in the deep-water Gulf and in the shallower waters of the continental shelf to depths as great as 33,000 ft (10,000 m) and temperatures as high as 475°F (250°C). At these depths the greatest unknown and most critical risk factor is reservoir quality. The ability to predict reservoir quality (porosity and permeability) and physical characteristics of ultradeep reservoir rocks has lagged behind our understanding of the other parts of the petroleum system, such as depositional facies, traps, and petroleum migration. Several Bureau colleagues and I conduct research (the Deep Shelf Gas project) that is focused on reservoir quality in ultradeep sandstones in the Gulf of Mexico. The unknowns that remain about reservoir quality in ultradeep drilling targets make this a critical area for continued investigation.

Got Data?

Caroline L. Breton



For those of us working in a scientific field, the answer to the title question is surely “yes.”

Want more out of your data? “Yes,” again.

Can the data be tied to a geographic location? At the Bureau, often the answer again is “yes.”

Now let’s talk GIS (geographic information system).

The simplest of definitions goes something like this—GIS is a system of hardware and software used for the storage, retrieval, mapping, and analysis of geographic data. In addition, GIS requires personnel to manage the operations and data with which to work. This simple definition doesn’t quite capture the magic, the power that is GIS, for it is a system with tremendous built-in functionality, full customizability, and an active community of developers launching new tools and applications continuously. It would take forever to explain it all, so let’s skip the technical details and see what it can do for you!

Do you have data in multiple formats that if integrated would have more meaning, more value? Do you need data-management or data-storage solutions? Do you need analytical capabilities or 3D modeling? Would your ideas be better communicated on a map or by visualization? Do you need material for further investigation, presentations, or publication? Do you need to provide data products to partners or the public? Although these seem like a lot of questions and a



lot of needs, they are only a sample of the questions and problems that can be solved by implementing GIS.

At the Bureau, I participate in multiple projects and generate a variety of products using GIS. The work is currently largely conducted at

the PC level, at which individuals organize and manage personal databases. The case has recently been made to move toward a Bureauwide GIS, taking data to the server level, at which access to the data is expanded. Benefits would extend to Bureau researchers, staff and students, our partners in academe and industry, and the public we serve—especially by increasing efficiency across departments and between projects because the data are not bound to an individual workstation. Data are held to a higher standard, and metadata—descriptive and source information about the data—are required. Not only data but projects, templates, methods, models, scripts, and tools can be shared as well, greatly decreasing duplication of efforts.

And just think—what if a move toward an institutionwide GIS spawned organic formation of an active community of GIS users? More power to more people! As people learn and share GIS data, knowledge, and tools, then time and energy are freed up for higher pursuits of all kinds. More power to more people! Data will no longer get us down; instead we will be empowered. More power to more people! Peace!

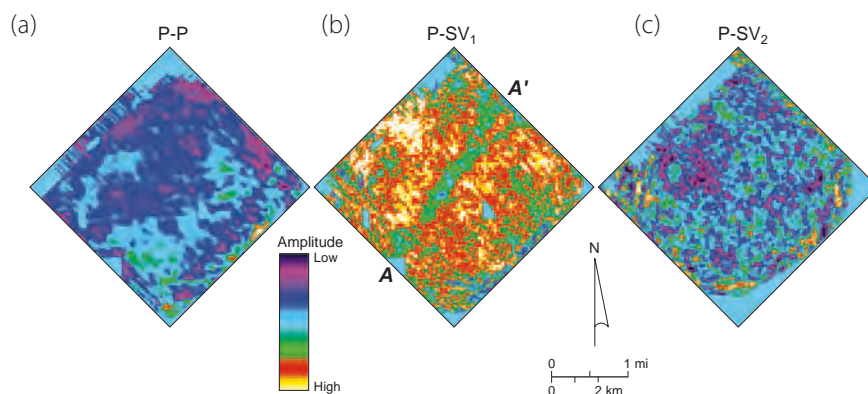


Deep Feelings and Picking Peaches

Dr. Bob A. Hardage

I am an applied geophysicist developing deep feelings about rocks. I don't mean that I get emotionally attached to rocks, but that I develop technology that "feels" subsurface rock layers in ways that allow better rock-fabric description. The

S waves to evaluate rocks, we feel rocks in three directions just like shoppers feel peaches. When we image rocks using both P and S seismic waves, we naturally get more rock-fabric information than we do if we use only one seismic wave (whether



P or S). Using one seismic wave to feel deep rocks is equivalent to doing only one pinch of a peach. A shopper *may* select an excellent peach on the basis of only one feel, but better choices result when multiple feels are made in different directions. The same conclusion applies to evaluating deep rocks. One deep feeling of

rock layering may lead to

rock fabric has to be evaluated without my seeing the rocks or physically touching the rocks. To feel buried rocks, I press them, shake them, squeeze them, and flex them using seismic waves.

a correct geological interpretation, but multiple feelings in orthogonal directions should result in better interpretations.

The technology I have developed imitates what shoppers do at the store when trying to decide which peach to choose. Usually meticulous shoppers will pick up a peach and gently press it between thumb and forefinger from two or three directions before deciding whether it has the desired internal fabric for taking home. Similarly, you get a better sense of rock fabric if you feel rock layers in two or three different directions rather than one. In the seismic world, this multidirectional feeling of rocks is done by causing both compressional seismic waves (P-waves) and shear seismic waves (S-waves) to pass through a targeted rock volume.

The figure shows reflection amplitudes from a deep-sandstone interval that was felt with a P wave and two orthogonal S waves. An important intrareservoir anomaly, A-A', was revealed by only one of these three rock-fabric-sensing directions. The P wave (a) felt the interval using a vertical displacement and could not sense the thin anomaly. The slow S wave (c) felt the interval using a horizontal displacement pointing almost east-west, and it could not sense A-A' across its narrow width. In contrast, the fast S wave (b) felt the interval with a displacement oriented almost north-south and reacted strongly to the long length of the anomaly. One deep feeling in only one direction is often insufficient to describe the internal fabric of a rock layer.

As P- and S-waves propagate along the same path through rock layers, S-waves (two different S-waves) displace each small rock volume along this path in two orthogonal directions, and each of these S displacements is, in turn, orthogonal to the direction a P-wave (only one P wave) displaces the rock. These rock displacements are the seismic equivalent of feeling rocks. By using both P and

I am a Senior Research Scientist at the Bureau and direct the Exploration Geophysics Laboratory (EGL). EGL's objective is to work with industry sponsors to develop and apply multicomponent seismic technology to an evaluation of Earth resources.

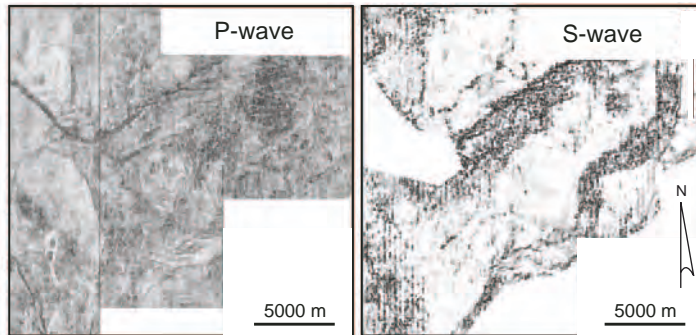
Boutique Seismic Exploration

Michael V. DeAngelo



I've been working as a geophysicist at the Bureau for the last 13 years. During this time I have been involved in development of multicomponent seismic technologies, with particular emphasis on interpretation and acquisition challenges. Many people ask, "Why would you use multicomponent (S-wave) seismic technologies instead of cheaper, conventional (P-wave), seismic technologies?" It is true that 3D conventional seismic, combined with horizontal drilling and hydrofracking techniques have added immensely to the proven reserves of the world, and the United States in particular. These technologies have been vital to the recent exploitation of massive shale-rock plays being pursued around the world. This is where the advantages of multicomponent technology have merit, however. Traditional seismic techniques can characterize the extents of these massive rock formations but cannot determine where the natural fractures occur within the shale formations or determine the orientation of these fracture zones. And an accurate picture of these characteristics of the subsurface target zone is crucial to development of a strategic well-bore plan that will maximize

hydrocarbon extraction and minimize any potential environmental impacts.



P-wave data-similarity time slice at 796 ms and S-wave data-similarity time slice at 1964 ms, depicting a "baseline" image used for comparison.

Multicomponent seismic technologies use the character of sound waves that travel through the Earth. After a source has been initiated, the sound wave travels in two modes. The P-wave is the conventional wave that is sensitive to changing rock density and velocities, as well as fluids trapped

within the rock formations. The second mode (multicomponent) is the S-wave, which is sensitive to the same rock density and velocities, but it is impervious to any fluids trapped inside the rock's pores. In addition, the S-wave mode will separate into two separate wave trains when it encounters fractures within the rock bodies. In such a case, we have techniques that can determine in what orientation the fractures are, as well as the amount of fracturing occurring in any given area. By comparing P- and S-wave data, we can determine whether subsurface anomalies are due to rock-property variations alone, or whether the rocks are filled with potential hydrocarbons—both of which create a clearer picture of the subsurface geology.



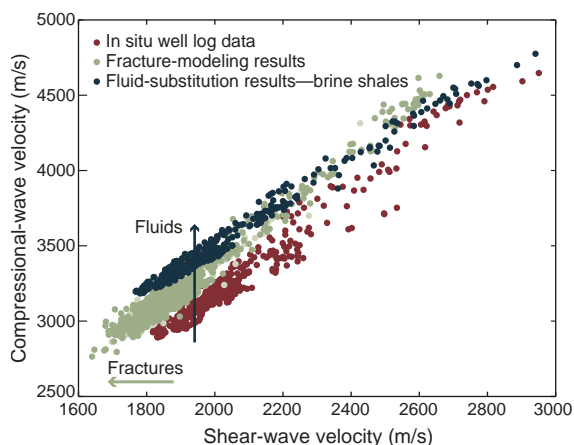
Unconventional Rocks!

Dr. Diana Sava

Are you unconventional? Well, I am—at least when it comes to rocks! Being unconventional is challenging, but also fun! My research goal is to use rock-physics theories to explain and quantify geophysical measurements of unconventional resources, such as tight-gas sands, gas shales, and even gas hydrates. Because of our growing need for more resources, coupled with the goal of energy independence,

we started exploring these unconventional reservoirs more extensively—only to discover new challenges, although new opportunities as well.

The research in which I am involved for the Exploration Geophysics Laboratory is part of a greater endeavor at the Bureau and at the Jackson School of Geosciences in general. Bureau researchers, in close collaboration with industry, now look at gas shales and tight-gas reservoirs from different geological and geophysical perspectives. Only by cumulative research that is aimed at studying rocks at different scales (from micro- to field scale), and by bringing together various disciplines, can we answer the challenges these unconventional resources raise: How can we better exploit these low-permeability reservoirs? What is the impact of natural fractures on fluid flow and production? How effective and safe is hydraulic fracturing? Can we monitor fracture development using seismic data? What is the impact of fluids and organic matter present in the shale? How does the large heterogeneity of shale mineralogy affect geophysical data and the uncertainty associated with our estimates? I am trying to answer some of



Compressional velocity versus shear-wave velocity for Marcellus shale for in situ well log data (red dots), fracture-modeling results (green dots), and fluid-substitution results (blue dots).

these questions using rock-physics theories to relate geophysical measurements to subsurface properties. And I use well logs and multicomponent seismic technology to characterize subsurface fracture networks, natural or induced, to predict fluid saturations in fractures and in tight rocks and to better understand the complex lithology of these unconventional resources. My focus is on Marcellus Formation shale. The conventional ways of using shear-

wave splitting or azimuthal variation of seismic amplitudes for fracture characterization in typical reservoirs are not applicable to Marcellus shale. This shale displays two orthogonal fracture joints, in which, when they exhibit similar fracture density, no shear-wave splitting can be observed. We now look beyond conventional wisdom for fracture characterization and use other indicators for fractures, such as overall shear-wave-velocity decrease coupled with compressional to shear-velocity ratios and seismic amplitude variations associated with cracked zones. Well log data and modeling results show how velocities can help differentiate effects of fractures and fluids in Marcellus shale.

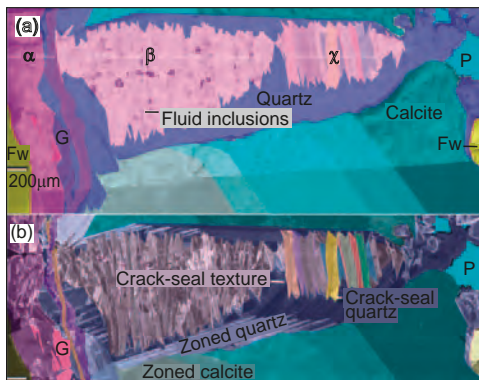
Hydrates, also on my menu—a dessert!—are a type of ice that can give you gas! Hopefully, lots of it! Seriously, though, predictions are very optimistic. My interest in hydrates is again to use rock physics to predict subsurface hydrate saturations from seismic and well log data, even though whether they are economical remains questionable. I think it is important to keep looking ahead, however!

Brittle Science

Dr. Stephen E. Laubach



A challenge for geoscientists is to understand fractures in the deep subsurface. Fluid flow in fractured rock is increasingly important in recovering water and hydrocarbon supplies and geothermal energy, in predicting flow of pollutants underground, in engineering structures,



Scanning-electron-microscope images of structural diagenetic textures within fractures. Linear feature in center is a cement deposit, a *bridge*, formed during fracture opening. Such bridges, discovered in Bureau research, allow researchers to measure key aspects of fractures, such as opening rate, that were previously inaccessible. Results can test predictive models and improve subsurface fracture diagnostics.

See S.E. Laubach, P. Eichhubl, C. Hilgers, R.H. Lander, 2010, *Structural diagenesis*: JSG 32(12):1866-1872 and associated theme journal issue.

and in understanding large-scale crustal behavior. Natural fractures, a major unknown in unconventional oil and gas reservoirs, can interact with engineered hydraulic fractures in surprising ways. Yet learning about fractures is not easy. Fractures are exceedingly hard to sample in meaningful ways, and models to date have been hard to test, partly because fractures formed by different processes can look alike—if analysts don't know what to look for. Meeting the challenge of accurate fracture characterization and prediction has been my mission. And breakthroughs have

come from looking at the old problem of fractures in new ways. Since the first scientific notice of fractures in the 1800's, the starting point for understanding fractures has been mechanics—a reasonable perspective given everyday experience. Rigorous application of fracture mechanics continues to yield insights. But for fractures in the deep subsurface, mechanics, no matter how complete, is inadequate. In the presence of reactive fluids like hot water, ubiquitous in the subsurface, chemical reactions are essential. Sedimentary petrologists study chemical reactions that convert sediment to rock—*diagenesis*—but typically neglect fractures.

Focusing on the geochemical reactions in fractures and surrounding rocks was a breakthrough that led to new, more effective and accurate ways of predicting and characterizing fractures—an approach I call *structural diagenesis*—a new research and training paradigm in sedimentary geochemistry and structural geology, perhaps a new discipline. Structural diagenesis is the study of the relationships between deformation or deformational structures and chemical changes to sediments. In high-temperature deformation research, the alliance of structural geology and petrology is essential. But no such alliance supports research and student training on the increasingly important structural and diagenetic phenomena in lower-temperature environments in sedimentary basins. Such an alliance—structural diagenesis—can help unlock knowledge about the low-temperature realm of sedimentary basins that is of great intrinsic and practical interest.

I am a Senior Research Scientist at the Bureau, where I lead the fracture and structural diagenesis programs. My research interests include unconventional and fractured reservoirs and microstructural, fluid-inclusion, and cathodoluminescence applications to structural geology and sedimentary petrology. I supervise graduate-student research in structural geology and diagenesis in the Jackson School. I am currently (2010–2013) AAPG Elected Editor and a member of the AAPG Executive Committee.



How Rocks Break

Dr. Peter Eichhubl

Continued access to affordable oil, natural gas, and groundwater resources is of concern for global economic development and maintaining living standards in industrialized nations. These resources occur in porous rock formations containing fractures and faults that formed by natural geologic processes. Natural fractures and faults can significantly affect production of hydrocarbons and groundwater from wells and, thus, economic access to these resources.

Fellow Bureau geoscientists and I have a fair understanding of how rocks break by fracturing and faulting under controlled laboratory conditions. Do results of these experiments apply to rock fracture and fault processes that occur under natural conditions at depth where hydrocarbons accumulate? Our observations from field outcrops and core samples obtained from outcrop to the micrometer scale using a variety of techniques—field observation, light microscope, X-ray and electron-beam imaging, and seismic imaging using acoustic waves—suggest that laboratory findings apply to natural faults and fractures found in subsurface reservoirs with significant limitations. For instance, natural fractures and faults display structural complexity not observed in experiments, including mineral-cement deposits reflecting fracture processes occurring under chemically reactive conditions difficult to replicate in the laboratory. Natural faults provide evidence of multiple deformation processes occurring in concert



Natural fractures in sandstone of the gas-bearing Nikanassin Formation in the Canadian Rocky Mountains. Fractures are partly open and lined with white mineral cement. Natural fractures similar to those observed in outcrop influence production of natural gas from nearby wells. Canadian toonie (\$2 coin) for scale.

that can be replicated in experiment in isolation but generally not as concurrent, interacting processes, as inferred for natural systems. These discrepancies suggest that laboratory experiments are fundamentally limited in replicating natural-rock-fracture processes. In my research team, we have performed microscopic analyses on mineral cement in natural fractures from gas reservoirs, suggesting that these fractures formed over periods spanning to 50 million years, with growth rates as slow as 0.02 mm per million years. These time spans are long

enough, and the rates slow enough, for the rock formation to undergo chemical and physical changes that interact with the fracture process. The longevity of these fracture processes and their interaction with chemical and physical changes to the formation challenge application of laboratory experiments to prediction of occurrence of fractures and faults and their impact on production of hydrocarbon and water resources. Our research addresses these challenges.

Both Bureau Research Scientist and Department Lecturer, I also lead the Energy Theme in the Jackson School and am the Bureau Managing Editor. Graduate students and postdocs under my supervision contribute to my research projects. I am Associate Editor of the *GSA Bulletin* and the *AAPG Bulletin*. Before UT, I did research at Stanford University and the Monterey Bay Aquarium Research Institute and held a faculty position at Texas A&M University—Corpus Christi.

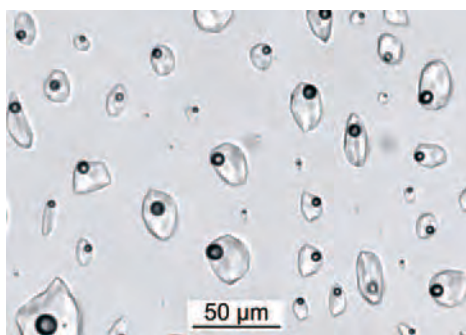
Fluids! Where? Everywhere!

Dr. András Fall



Water and other geofluids play a significant role in the physical and chemical evolution of the Earth. Fluids contribute to the transport of chemical constituents and heat to form new minerals and rocks, but the same transporting properties contribute to fluid-dominated erosional processes that destroy them. Fluid compositions take on characteristics of the surrounding rocks that are a result of interactions

between them. In continental sedimentary basins, fluids are associated with hydrocarbon deposits, but they can be a significant transporting agent in the formation of ore deposits. In deeper, crystalline environments, fluids have characteristics associated with metamorphic processes owing to long-term fluid-rock interactions. Fluids are present at tectonic-plate boundaries. Subduction zones represent environments where fluid components are recycled into the deep crust and mantle, and these fluids can significantly affect mantle rheology and evolution. The volume of fluids carried to deeper levels in subducted plates influences the rate and depth of melting that produces magma. Mid-ocean ridges and volcanoes return fluids to the surface. Fluids may even play a significant role in earthquakes as well. Pore fluids influence evolution and dynamics of the continental crust. And the deformation mechanism of crustal rocks is influenced by the presence of water, as well as by the magnitude of pore-fluid pressure. Water is the most important resource on Earth. Fresh water, such as in rainwater, streams and rivers, lakes, and groundwater, keeps humans alive; without it we would not survive for more than a week.



Fluid inclusions in fluorite from the Deardorff mine, Cave-in-Rock District, Illinois.

The oceans represent an important water reservoir that acts as an interface between the atmosphere and the near-surface hydrosphere, thus influencing global climate.

Knowledge about the composition and role of fluids in various geologic environments lessens with the depth of the environment. We can sample surface or near-surface waters without much

difficulty, but in deeper geologic environments, sampling becomes more difficult. We can, however, infer compositions and the role of fluids in these environments indirectly through mineral equilibria calculations or directly from fluid inclusions trapped in minerals.

My research interests focus on properties of fluids in the Earth's crust and application of these properties to solving various geologic problems using information available from fluid inclusions. These inclusions are droplets of fluid trapped as imperfections in a growing crystal or a healing fracture in a mineral, and they are one of the best tools for determining pressure, temperature, and composition (PTX), as well as the origin and timing, of fluids associated with formation of the host mineral and its subsequent history. My recent projects have focused on improving our understanding and use of fluid-inclusion microthermometric and Raman spectroscopic data in interpreting geological events, as well as the use of fluid inclusions in answering questions about fluid properties related to fracture opening and cementation in tight-gas sandstone and shale-gas reservoirs and outcrop analogs.



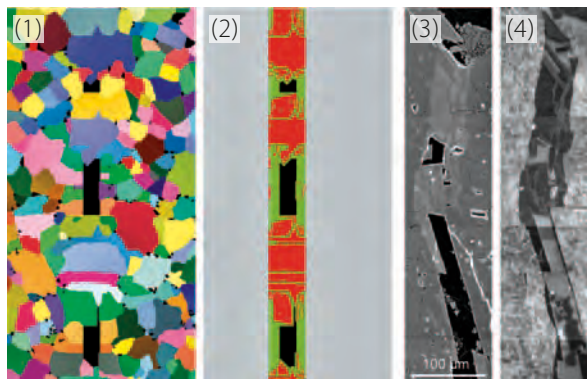
Fractures in Hydrocarbon Reservoirs

Dr. Julia Gale

My interest in fractures began while I was working on something else, as so often happens in scientific endeavors. I was looking at rock types and structures that develop because of relatively high temperatures and pressures during mountain-building events. Conspicuous fractures filled with large, attractive-looking crystals were present in many of the rock outcrops I worked on. I began some quantitative studies of these vein systems and quickly became aware of the work on fractures at

The University of Texas at Austin, and eventually I joined the team at the Bureau. Fracture geometries are commonly similar looking, independent of the scale of observation, and our group has a strong record of documenting this phenomenon in many different rock types and in explaining how it arises.

My first foray with the group was fieldwork in carbonate rocks in central Texas and Northern Mexico. In both cases, the fieldwork entailed my lying down on the rock on my stomach, eyeball up to a hand lens, measuring the widths of fractures and how far they were apart. These had to be robust datasets, so not a single fracture could be missed. I usually had a "scribe" to record the data so I would not lose my place, who would offer encouragement when the going got tough. In addition to fieldwork, I also use rock cores taken from hydrocarbon reservoirs several thousand feet below the ground surface. These offer a direct look at a reservoir, although there is a problem



How computer models can replicate natural fracture-cement growth. Model crystal domain geometries (1) and cement-growth rates (2), together with corresponding natural examples of cement microstructure (3, 4), shown for moderate opening-rate simulation resulting in bridge structures where growth is fast and slot-shaped pores associated with slower cement-growth rate. Images in 3 and 4 ~100 μm wide. Gale, Lander, Reed, Laubach, 2010, Modeling fracture porosity evolution in dolostone: JSG 32:1201-1211.

with sampling bias. The core is typically only 4 inches across, and we are trying to characterize fracture patterns over the scale of kilometers. How do we move from one scale to the other? This is where fractal-size relationships come in, and the prospect of using microfractures to predict properties of macrofractures forms a central concept of my work. Recently my focus has shifted to fractures in shales, driven partly by the surge in hydrocarbon production from these rocks. Fracture studies

in these unconventional reservoirs require different methodologies, although the fundamental approach remains similar.

A strength of our group is that it encompasses people with different specialties. I work with Dr. Jon Olson and his students, whose developments in geomechanical modeling allow prediction of fracture patterns on a scale larger than that of core. Their methods are complementary to my rock observations. Besides observations of cores, I also use thin sections to document fracture-cement relationships and unravel fracture timing. I use light and electron microscopy to image the fracture cements. In the illustration, images of fractures and their cements on the right are replicated using computer-modeling techniques of cementation patterns in fractures developed by Rob Lander, a Visiting Scientist at the Bureau, who collaborated on this work.

The Tale in the Rocks

Dr. Estibalitz Ukar



I like to think of myself as a “rock whisperer.” I sit there for hours at a time—in the lab, or, where I am even happier, in the field—and I wait for the rocks to talk to me. If I listen carefully, they always do. They have amazing stories to tell, so I just focus and listen.



Listening to rocks in Alberta Foothills, Canada.

I like two types of stories. Some of my favorites are about how these rocks came to be—from an assembly of loose sediment, crystallization from hot magma, solid transformation through processes that are hard to picture, or a combination of some—or all—of the above, possibly several times. Others are about the deformation these rocks have suffered (or enjoyed), from burial through exhumation, to get to where they are today.

After exploring the exciting world of high-pressure metamorphism for my Ph.D., I tried exploring a shallower world, which is equally fascinating. In my time as a Postdoctoral Fellow at the Bureau, I have been able to combine my passion for petrology, structural geology, and tectonics in a study of coupled structural and diagenetic processes

governing the formation and cementation of fractures in fold-and-thrust belts. Deformation leads to fracturing, and fractures lead to enhanced storage for goodies such as oil, gas, and water. The combined approach of accounting for geochemical reactions in rocks instead of geomechanics

alone in a discipline called *structural diagenesis* here in the Fracture Research and Application Consortium (FRAC) has resulted in a breakthrough in our hunt for sweet spots in unconventional reservoirs. Our research has provided new approaches and tools for exploration and has greatly improved our predictive capabilities of fracture-network characteristics and distribution in sedimentary basins.

I travel the world looking for outcrops that contain the same fractures as reservoirs in the subsurface because, until we come up with technology similar to Superman’s X-ray vision, it is the best way to closely examine what is down there. “But wait a minute!” you may think. “Everywhere I look I

see fractured rocks! Why can’t you just pick up a piece from your backyard?” Well, because then my job would not be as fun! And also because most of the fractures that we see at the surface are the result of weathering and they have no influence on the storage of goodies in the subsurface. Later, once we locate and work on appropriate outcrops, we bring samples back to the lab, where I get to play with them! SEM, CL, EBSD, EMPA, FI, and XRD are only some of the state-of-the-art capabilities available at the Jackson School that make our endeavor of deciphering the story behind the opening and cementation of these fractures even possible. But listening to the stories these rocks have to tell is the key to making informed decisions that influence not only production but also the safety of our environment for a better future for all of us. I will keep listening.



Flow Drives Everything!

Dr. Peter Flemings

When I finished studying stratigraphy in graduate school, I saw a lot of stratigraphers, but not many *people* studying how stratigraphy and fluid flow couple. So began a 20-year journey that I am still on.

Today I study how fluids impact geological systems. My research spans the applied and the fundamental. I run UT-GeoFluids, an industry-sponsored consortium that explores flow and overpressure in sedimentary basins. We do field studies of overpressured systems, we develop models of how stress and pressure interact, and we perform geomechanical experiments in the lab. Two summers ago I put all these ideas to work as part of the government's well-integrity team on the BP Macondo well blowout.

I love to drill wells, and, as an academic, I do that through the Ocean Drilling Program. I've drilled wells to study shallow pressure in the Gulf of Mexico, how flow drives landslides on the Atlantic margin, and how pore pressure impacts development of large earthquakes in offshore Japan. There is nothing so satisfying or so frustrating as testing your ideas with the drill bit.

The best part of my day is watching our research group work together to discover new things. We've got postdocs, research scientists, project managers, technicians, and graduate and undergraduate students all asking questions, learning new techniques, and making new discoveries. At the root of every question is the study of fluid flow in stratigraphy. These folks teach me things every day, and I try to keep up.



Photo courtesy of Bill Crawford, the USIO of the Integrated Ocean Drilling Program. <http://iodp.lam.edu/starfall/>.

I bring our discoveries to the classroom. I teach undergraduates petroleum geology, and I stress the enormous importance of fluids. I teach graduate students how flow drives faults, landslides, deep-sea vents, hydrate formation, and compaction. I love to mix the classroom with the field through trips to west Texas and California.

Flow and Deformation in Porous Media



Dr. Athma R. Bhandari

My research is focused on flow and deformation in porous media. In my studies, I am trying to understand the underlying mechanics of observed macroscale behavior of porous media, both in the laboratory and in the field.

One question I have been pursuing is how much natural gas we can produce from virtually tight gas shales. For this question to be answered, the mechanics of gas transport in these rocks need to be understood. I conduct permeability experiments in the laboratory on shale-core samples at stresses similar to those of in situ conditions and investigate gas-flow behavior. Understanding the flow through nanopores requires subnanoscale thinking! And this is what draws me to this research.

Why is it that natural slopes, boreholes, fault gouges, earth dams, building foundations, retaining walls, etc. sometimes fail? An answer to this question requires an understanding of the microscopic physics of deformation and fluid-flow

behaviors in soils and rocks. In another technical area of my research, I develop digital image-based techniques for characterizing the evolution of grain-scale processes governing deformation of nonuniformities and their evolution. I also characterize internal microstructures using microscopy and elastic and plastic mechanical properties of earth materials in the triaxial cell.



Barnett shale core plug used for gas-permeability measurement.



A natural sand specimen developing a failure plane (shear band) during a triaxial test.



Mud Pies to Consolidometers

Peter Polito

Leaning against the railing on the bow of the JOIDES Resolution was a solid reminder of why I love my job. We had just passed through the Mona Passage, the sun was setting, flying fish were racing in and out of our bow waves, and we were only days away from testing the latest Integrated Ocean Drilling Program (IODP) technology designed, in part, by our lab.

I manage the Geofluids Lab at the Bureau, one of two labs in the GeoFluids consortium, a joint UT-MIT research group. We are dedicated to understanding how fluids move through the crust, from shallow marine sediments on down to tight, low-permeability shales. Much of the work we do in the lab requires equipment that cannot be bought off the shelf; instead, I build components from scratch. Through planning, testing, failing, and overcoming, the laboratory staff and I are able to create systems and experimental apparatuses that allow us to answer questions that previously were unattainable. But we don't just build experimental set-ups; we also make our own rock! Using a technique refined by our consortium, we make our own mudstones through a process called *resedimentation*. Through this process we take dried clays and silts, combine them with water and salt, remove air bubbles, pour them into large tubes, and incrementally add weight over a period of weeks to months. In the end we have a mudstone not too different from those found in the Gulf of Mexico. With these samples we can run



Discussing water and sediments interactions in the Henry Mountains, UT.

a suite of experiments to help us to better understand how sediment changes and evolve as it is buried in the Earth's crust.

Running lab experiments is only part of what I do. A large portion of my time has been spent modifying and refining our remotely deployable pressure and temperature probe—the T2P. The T2P is designed partly to help us link our discoveries in the lab with the real world. We use the T2P by lowering it through the drill string of the JOIDES Resolution. When it reaches the bottom, the drill string is pumped full of seawater, driving the probe into the formation below. While in the formation, the tool's data acquisition system is recording pressure and temperature, which helps the onboard scientists understand the conditions under which the sediment was deposited and how it has evolved. By repeatedly deploying the tool

as the borehole is deepened, we can construct a pressure profile providing a glimpse into the past. In using field data in conjunction with laboratory-derived models, we are able to make predictions about what pressures will be like in the deep ocean. With this knowledge we can identify high-risk regions of overpressure that may be susceptible to failing (via underwater debris flows) or may cause risk to industry activities. I take pride in knowing that what I do today will not only advance our science, but will help people make informed decisions. It doesn't hurt that I have a blast in the process.

Photo courtesy of Lindsay Olinde

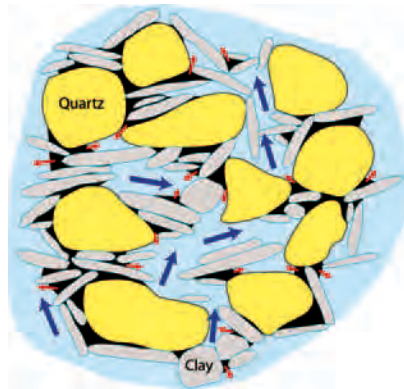
Following a Water/Gas Molecule through Mudstones

Dr. Julia Reece



Several questions have captured my interest in subsurface processes such as deformation and fluid flow: How does squishy mud from the ocean floor become a hard rock? How does composition affect physical and mechanical properties, as well as the microstructure of these rocks? How do fluids move through soft muds, and how is gas transported through tight-gas shales—by connected pore throats and/or a fracture network? If through fractures, are these real or coring induced? I study materials ranging from shallow, soft muds to deeply buried, low-permeability, hard rocks. This type of research is important for prediction of overpressure and geological hazards (for example, submarine landslides), geological CO₂ storage and sequestration, hydrocarbon trapping, and production from unconventional oil and gas reservoirs. The processes involved in transforming a mud to a hard rock are complex. As a mud becomes weighed down by overlying sediments, it reaches larger subsurface depths and experiences higher temperatures and different fluids, resulting in a microstructure and physical properties that evolve with depth. By performing a multidisciplinary study on (1) intact mudstone cores from various

depths and (2) synthetically prepared mudstones of various compositions and consolidated to various stresses, I can address many of these questions.



Cartoon illustrating water flow through a mudstone. Large, connected pore spaces (light-blue) create key flow paths (blue arrows) for water molecules. Smaller pores (black) contribute to flow by diffusion (red arrows) into larger pores.

A large part of my current research is on gas shales. These are fine-grained sedimentary rocks that have trapped natural gas, which has become an important energy source in unconventional reservoirs. I conduct permeability measurements on core plugs of gas shales in the GeoFluids Lab at the Bureau and integrate them with microscale imaging and pore-size analysis to help me understand mass transport in tight systems. This project is a wonderful opportunity to work and communicate with researchers and students from inside and outside our research group.

I received my Ph.D. from The University of Texas at Austin in 2011 and am currently a Postdoctoral Fellow at the Bureau. My research on soft muds is supported by the Integrated Ocean Drilling Program (IODP), and the project on hard rocks is a Shell-University of Texas Unconventional Research (SUTUR) project in collaboration with the Department of Petroleum and Geosystems Engineering titled “Mass Transport in Gas Shales,” which is funded by Shell.



Jill of All Trades

Tessa Green

Finalizing proposals, editing web pages, keeping on budget, tracking publications, organizing databases, communicating with sponsors, scheduling meetings, all while making sure Peter Flemings has plenty of caffeine, is a typical day in my job. As the Project Manager for Peter Flemings' research group I am responsible for a myriad of tasks.

The UT GeoFluids Consortium, an industrial associates program at the Bureau, is my primary project. UT GeoFluids studies the state and evolution of pressure, stress, deformation, and fluid migration through experiments, models, and field study. This industry-funded consortium is dedicated to producing innovative concepts that couple geology and fluid flow. Results are used to predict pressure, stress, trap integrity, and borehole stability. The UT GeoFluids team combines geoscientists at U.T. with geotechnical engineers at MIT. My job is to support this research by taking care of the logistics that

are involved in day-to-day operations, marketing consortium accomplishments, and running the annual consortium meeting. I support 20 staff and students between UT and MIT.



In addition to UT GeoFluids, I am the Project Manager for Peter Flemings' SUTUR project, Mechanisms of Gas Flow in Shale, and his Department of Energy project, Controls on Methane Expulsion during Melting of Natural Gas Hydrate Systems.

I keep these projects on task and budget so that they can meet their research goals.

I bring many years of project-management experience to the Bureau. I began my career in the arts as a stage manager in theatre and then moved into production management of television and film. Although my background isn't rooted in science, I enjoy working at U.T. in the environment of learning and supporting research at the Bureau.

Making Rocks Talk

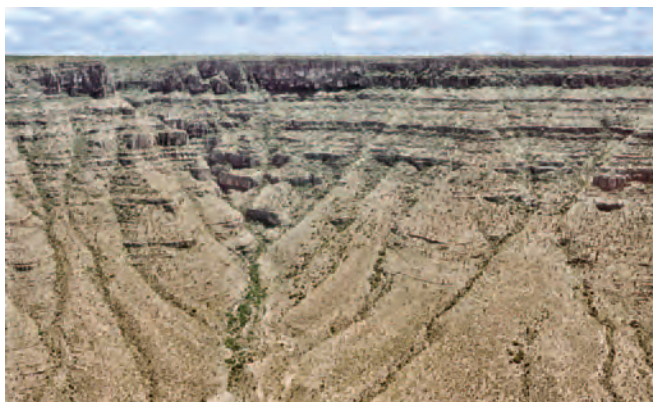
Dr. Steve Ruppel



Rocks are Earth's history books. They tell us about past climates, times of mountain building, where rivers ran, how deep oceans were, where organisms lived, and more. They also allow us to measure rock properties, such as particle sizes and types, pore types, porosity, and permeability—crucial in defining rocks that form hydrocarbon and water reservoirs.

Determining how rocks vary also helps in constructing predictive models when definitive data are lacking.

To interpret rock history, we require access to outcrops or cores from subsurface wells. Outcrops provide the best information because of their sheer size and volume. From them we can define geographic (horizontal) and stratigraphic (vertical) changes in rock character and interpret them by comparison with modern environments of sediment accumulation. Cores suffer from being essentially one dimensional and typically widely spaced. However, they commonly provide more relevant data about subsurface reservoir systems. In reservoirs, we want to integrate core data with information and models derived from outcrop and modern environments. Cores also provide data necessary for calibrating borehole geophysical logs, which, when calibrated, are the most abundant data type in reservoirs. Collectively, cores and logs can be used to build a comprehensive, 3D picture of rock character and variability over large areas. Reading this history and character from outcrops and cores requires a multidisciplinary approach to data gathering, beginning with megascopic and microscopic descriptions of rock components



Permian-age carbonate-rock outcrops, Sierra Diablo Mountains, west Texas. Large-scale rock exposures (1,500 ft high, 3 mi long) allow geologists to collect data used in unraveling conditions under which the rocks formed—crucial to an understanding of rock variations in subsurface hydrocarbon/water reservoirs.

(grains, fossils, pores, cements). In carbonate systems, these techniques can be sufficient to define facies architecture—rock-type composition and distribution—and provide insights as to distribution of key reservoir properties (permeability and saturation). Shales, especially those of economic interest because of the hydrocarbons they contain, require more diverse, sophisticated

approaches to data collection and interpretation. For these rocks, we complement conventional investigation techniques with X-ray fluorescence and diffraction analyses to define mineral types and distribution. We utilize scanning electron microscopy to image nanoscale pores and particles that compose these rocks. Only with these methodologies can we define key rock attributes

My current studies are a continuation of research I have been carrying out in sedimentary-rock systems (initially in carbonates and more recently also in shales) since 1981 at the Bureau, where I am a Senior Research Scientist. Interactions with graduate students in the Jackson School, through teaching and thesis supervision, and with my Bureau colleagues, have been crucial to my continued growth as scientist and interpreter of Earth history. I currently direct the Mudrock Systems Research Laboratory (MSRL), a consortium of oil and gas industry sponsors. Our goals are to develop new paradigms for understanding processes responsible for shale deposition and for defining and predicting variations in rock properties and patterns of accumulation of hydrocarbons found in some of them.

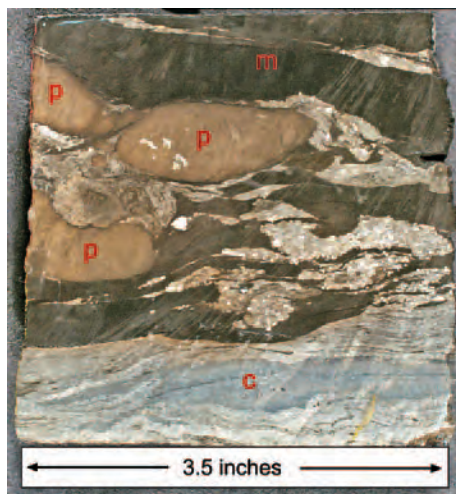
Foot by Foot through the Lower Permian: A Core Story



Robert Baumgardner

Describing 858 ft of continuous core is not everyone's idea of fun. When much of it is dark, apparently featureless mudrock, then the task seems even more onerous. But, once begun, the work takes on a certain appeal, challenging me to pay attention, to learn to read the history of the rock. Day by day, as I inch my way up the core, scratching it, applying drops of hydrochloric acid, spraying it with water, and peering at it with a binocular microscope, the core reveals its secrets. I begin to notice patterns. Subtle features that weren't especially interesting at first take on added significance as they appear again and again. Phosphatic nodules, carbonate concretions, and other oddities send me to the literature, searching for clues to what I'm seeing.

Among the observations necessary for scientific study, for conclusions regarding the character and origin of these economically important, oil-bearing rocks, there is room for wonder. One day I find a tiny ammonite shell that settled to the quiet seafloor more than 270 million years ago. And here it is, in the sunlight, again. Clusters of pyrite crystals look out of place sparkling in the midst of drab mud. What a strange world this is, where fine-grained sediment accumulates uninterrupted for centuries (at least 10,000 years per foot, by my reckoning), where my concept of 'seafloor' loses its meaning because the boundary between sediment and water is only a gradual shift in the balance between muddy water and watery mud. Yet, here and there, the rocks show surprising evidence of energetic deposition on a firm substrate. Within



Core showing features in basal mudrocks.
c = chert lens (blue) in wackestone/packstone.
m = mudrock. p = phosphatic nodule.
Small-scale, soft-sediment deformation visible between phosphatic nodules and underlying wackestone/packstone.

the enclosing matrix of flat-lying, silty sediments are conglomerates containing carbonate clasts bigger than both my fists together. I'm 40 miles from the Permian shore, far below the reach of storms. What process brought this cobble here? Elsewhere, wildly deformed layers of sand and mud are evidence of what—an undersea avalanche, an earthquake, local shifting of the weirdly gelatinous 'seafloor'? And so it goes, foot by foot, until I reach the top of the core.

Taken together, these observations indicate that the mudrocks were deposited and preserved in anoxic, sometimes sulfidic conditions, which preserved

organic matter, the source of hydrocarbons. The contrast in brittleness between interbedded conglomerates and mudrocks provides opportunities for enhanced recovery of those hydrocarbons through hydraulic fracturing. But interconnections created by deformed bedding may be 'thief' zones, allowing fluids to leak away.

The purpose of this core-based study is to improve our understanding of these and other basal mudrocks. Mudrocks, broadly defined, are the most common sedimentary rocks on the planet. They are the subject of ongoing research by the Mudrock Systems Research Laboratory group at the Bureau. Because mudrocks have become economically important sources of oil and gas, studying them serves a dual purpose: to help explain the basic geology of Earth and to enhance the production of hydrocarbons from mudrocks in Texas and elsewhere around the world.

Your Rock Deposits are Safe with the Swiss Sedimentologist

Dr. Gregory Frébourg



Although I try hard to use “y’all” whenever appropriate and pronounce “oil” as “all,” my slight French accent (and maybe my signature satchel?) gives away my European origin a kilometer—no,



Photo courtesy of David Smith.

wait—a mile away, even though it is finally “legal” for me to wear cowboy boots and drive a pick-up truck (try to do that where I’m from!). In September 2010 I moved from my hometown of Geneva, Switzerland, where I

had earned all three college degrees to work as a Research Associate at the Bureau.

Under pleasant, sunny, Texan skies (my hometown is cold and rainy most of the year), I do fundamental and applied research in sedimentology. Although I sometimes work with the State of Texas Advanced Resources Recovery group (STARR, PI: Bill Ambrose) and Reservoir Characterization Research Lab (RCRL, PI’s: Charlie Kerans, Bob Loucks), my time is devoted mostly to the Mudrock System Research Laboratory MSRL group (PI: Steve Ruppel).

MSRL observations reveal that pelagic mudrocks can and do accumulate under high-energy settings generated by the influence of bottom currents, which contradicts the paradigm equating fine-grain sediment to low-energy deposition. Resulting sedimentary dynamics create lateral variations and internal heterogeneities on several orders of dimensional scale, which can have a strong

influence on the exploitation of hydrocarbons in these rocks. My input as a Research Associate in the MSRL consortium is to explain depositional dynamics of these fine-grained sedimentary systems and reconstruct their depositional environments to help predict rock volumes prone to hydrocarbons accumulation—or not.

If nature is not complicated, it is complex. My everyday job makes me feel like a naturalistic Sherlock Holmes, investigating every possible hypothesis, gathering clues, using all the possible tools I can, considering multiple points of view, and, especially, multidisciplinary approaches. If working on a computer is inevitable nowadays, I am lucky to be able to go to the field fairly often, where I can hone my interpretation skills through challenging and constructive debates with my colleagues (and, occasionally, my abilities for survival when dangling from a rope, collecting samples and making observations on a west Texas roadcut).

I will not hide my dark little secret: micropaleontology, especially foraminifera, is one of my favorite things. The shells of these single-cell

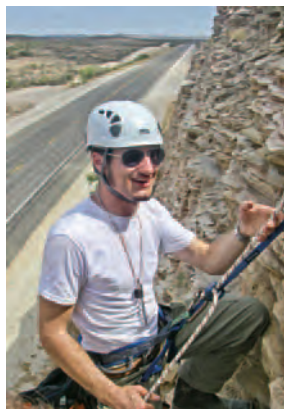


Photo courtesy of David Smith.

organisms not only have biostratigraphic potential, but they also carry a strong paleoenvironmental value, which can be invaluable, especially when working on core. I would like to develop a little micropaleontology-oriented group.

Finally, I have a passion for teaching. For me, being part

of the Jackson School is an honor, and I hope one day to join that crew of top-notch faculty and professors, who make the School great. That is, if students can deal with my accent....

Evaluating Basins for Petroleum Potential



Dr. Ursula Hammes

Evaluation of basins worldwide for their petroleum potential using techniques ranging from large-scale seismic interpretation to investigation of nanopores in mudrocks is crucial to the discovery of conventional and unconventional hydrocarbons. For the past 12 years I have been doing just that—conducting research investigating various sequence stratigraphic, sedimentologic, and diagenetic problems in different sedimentary basins in Texas and Germany. I have also served as co-PI of a Texas State-sponsored project known as STARR (State of Texas Advanced Resource Recovery)—a project designed to help oil and gas operators in Texas recover more hydrocarbons using advanced reservoir characterization, seismic interpretation, and research techniques. This project has allowed me to be involved in many intriguing plays in east and west Texas and the Texas Gulf Coast. Being part of applied projects in which we actually see our ideas being executed in the form of wells being drilled on the basis of those ideas is one of the unique and exciting benefits the Bureau has to offer.

Another positive aspect of working at the Bureau is the opportunity to conduct research on stimulating projects in different areas. I recently spent a year working at the University of Potsdam on a research assignment sponsored by the Mudrock Systems Research Laboratory (MSRL) consortium and the University of Potsdam, Germany. I was evaluating the Upper Permian Zechstein Formation of the Southern Permian Basin in Northern Germany for its unconventional reservoir potential. My new research direction, in conjunction with the MSRL consortium, has led me to explore mudrocks as unconventional reservoirs using techniques applied in conventional basins. These shale- and oil-bearing mudrocks are contributing to a substantial supply of oil and gas, and results are to be published in esteemed journals on our cutting-edge research in mudrocks.

For 11 years I have worked in various positions at the Bureau as Research Associate. I received the Jackson School Outstanding Research Award as a result of the success achieved by the STARR team, and I have been acknowledged by numerous other Best Papers, Presentations, and Posters at local and regional meetings. I am currently the elected GCSSEPM president, and I regularly volunteer at local and national societies as both session chair and distinguished speaker.



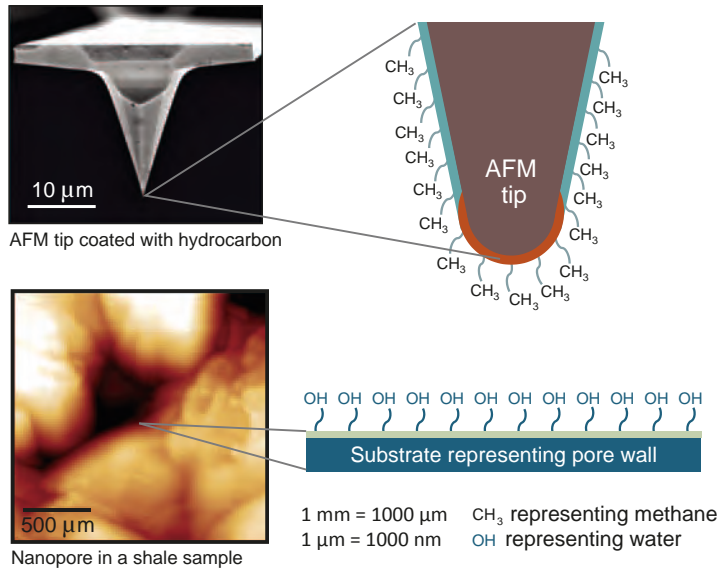
Photo courtesy of Nora Goldhammer.

Nanoscience in the Geosciences

Dr. Farzam Javadpour



Nano means one-billionth and *nanoscience* is the science of matter at the nanometer scale. The diameter of a human hair, for instance, is ~50,000 nm (nanometers)—to give you an idea of the scale. Study at such a small scale is fascinating, but it is challenging as well. At the large scale, certain complexities in the system can be neglected to simplify researchers' system of interest; however, at the nanoscale, complexities, must all be considered for our system of interest to be understood and modeled correctly.



(top-left: Scanning electron microscope (SEM) image of an AFM cantilever and attached tip); (top-right: schematic zoom-in image of the tip nose coated with methane molecules); (bottom-left: AFM topography image of a nanopore in a shale Sample); (bottom-right: schematic zoom-in image of the nanopore surface coated with water molecules).

My research is studying human-made and natural nanosystems, with a focus on energy, environment, and geosciences. Those in my group study transport of engineered nanoparticles (NP) in underground oil reservoirs and saline aquifers, and this research is a part of a larger research program overseen by the Advanced Energy Consortium (AEC), which is a consortium sponsored by major oil and service companies. After 3 years of hard work and many failed attempts and invaluable

learning, we have successfully modified an atomic force microscopy (AFM) setup for measuring the interactive forces between NP and different interfaces such as minerals and oil-brine contact surfaces so as to reveal the attachment and final retention of NP to the mineral grains in petroleum reservoirs.

One fascinating natural nano-system is the fast-growing shale-gas enterprise worldwide. In our recent studies we have identified extremely small pores (as small as 10 nm!) in shales that allow for gas and liquid flow. Gas flow through

these tiny pores is complex, and the legendary Darcy equation may not be valid in shales. In my research group we have developed new equations that govern gas flow in shales, and we continue to improve our model. Another intriguing topic is liquid flow in shale systems; we have been using AFM to measure interactive forces between fluid molecules and pore walls so as to include these forces in newly developed flow equations for liquid flow in nanopores of shale systems.



Rock History Written in a Very Tiny Script

Dr. Kitty Milliken

How is it that loose sand and mud, as you can find in a river, on a beach, or on the ocean floor, turn into hard rock? Why are certain properties of, say, sand on a beach versus sand of similar composition

buried deep in an oil reservoir so different? Why do some rocks in the subsurface have holes in them that host extractable oil, gas, or water, while others do not? Engaging in these seemingly simple questions has provided me with fascination and employment for nearly 40 years and will keep me, my students, and numerous colleagues busy for a while longer yet. Chemistry, physics, and biology all enter into the story of how sediments become rocks (lithify) and change their properties in response to conditions in the subsurface (undergo diagenesis).

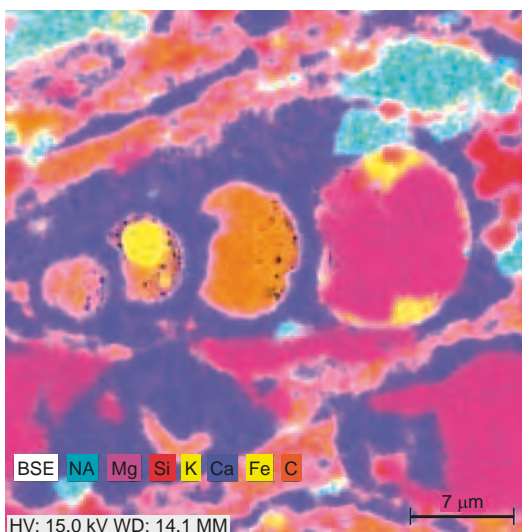
The processes involved take place across depths ranging from the surface to several kilometers into the crust and, most important, occur across a history that can span millions of years. Thus, this area of investigation has a certain eclectic appeal—you get to call on all the major areas of science and to work on samples from modern environments, outcrops, and the deep subsurface and, most important, engage in riddles that entail the wondrous complications of deep time. The historical aspects of the problem generally require that you cannot rely solely on

methods of bulk analysis, and, thus, it's necessary to interpret sequences of events by actually looking at the rocks. "Looking" in this case means

microscopy, which, for the materials that I study, produces images of great beauty that, to me, are rendered even more appealing for the meanings they carry. Deciphering the history of earth materials (sandstone and shale, mostly) is satisfying in itself, but it's important to note that knowledge about subsurface processes can be applied in a predictive way to bring efficiencies to exploration for oil, gas, water, and subsurface storage sites and, thus, make these resources cheaper and more widely available and the search for them less harmful to the environment.

At the Bureau, and as an instructor and

member of the Graduate Studies Committee in the Jackson School, I work with a multidisciplinary community of researchers and students to integrate microscale imaging and analysis so as to engage the problems described above. Much of my work on harder rocks from the deeper subsurface (mostly in oil or gas shales) is supported by major petroleum companies, and my work on younger, softer mud is carried out in connection with the Integrated Ocean Drilling Program (IODP).



HV: 15.0 kV WD: 14.1 MM

Foraminifer shell (dark-blue) with chambers (former pores) filled with organic matter ("dead oil," orange) and minerals (pink, yellow, and aqua) precipitated from fluids in the subsurface.

In the Nanogeosciences Lab

Dr. Zahra Mohammadi

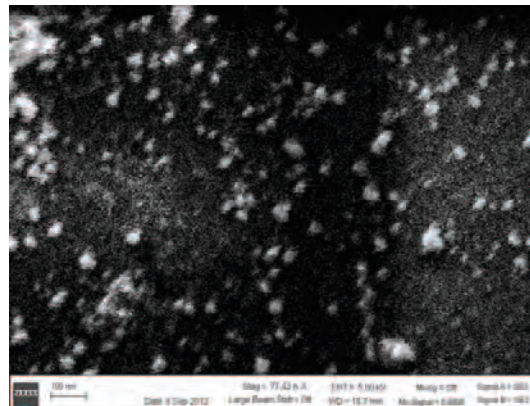
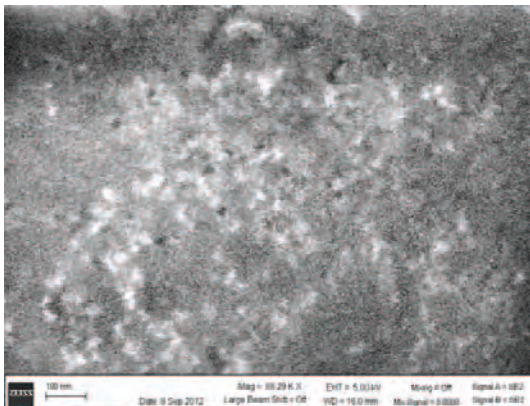


Dealing with the unreachable is what I enjoy most. I believe that the human body and geological systems are very much alike when it comes to collecting data and coming to an understanding of how these systems work. That is why I am using the same principles that are used in drug delivery and biotechnology in my study of geological systems.

I work in the Nanogeosciences Lab at the Bureau, where we use nanoparticles to learn about the phenomena happening within geological systems. As part of my work, I use atomic force microscopy (AFM) to study the interaction between nanoparticles and different minerals. The main goal in this project is to predict the fate of nanoparticles after they are injected into any geological system. This is done mainly through creating lab core samples into which we carefully inject nanoparticles; after collecting nanoparticles at the other end of the core, we are then able to

decide how many of the nanoparticles are retained by the core. Furthermore, we can decide which factors have the most effect on the retention of nanoparticles. The beauty of using AFM advanced technology comes into picture where we can study the interaction of nanoparticles with materials within reservoirs even before injecting them. This enables us to choose the material that interests us most. As an example, in some cases we would like to have nanoparticles with relatively low retention, so we can run an AFM experiment and find the deposition rate between nanoparticle and the mineral of interest. In this case we would have a fairly realistic estimation of the retention of nanoparticles before we run a time consuming core flood experiment.

I enjoy being involved in different projects and take pride in knowing that what I do matters.



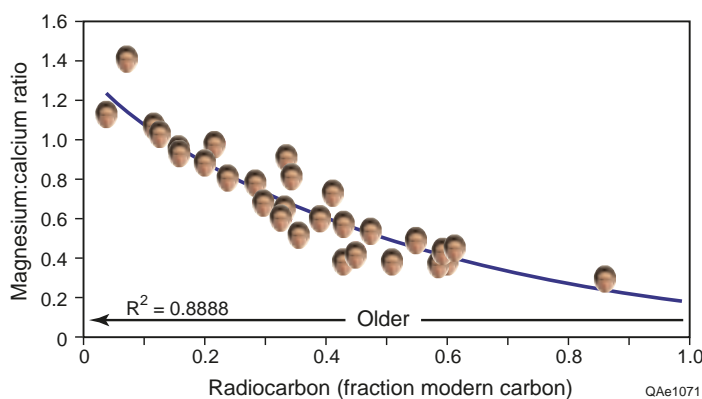
Research in Mudrock Stratigraphy and Quantification of Aquifer Recharge



Dr. H. Seay Nance

I've always enjoyed finding innovative solutions to problems, and developing descriptions for mudrocks is a perfect opportunity. Mudrocks of Paleozoic age are the focus of much of the reenergized hydrocarbon prospecting

activity in the Permian Basin region. These exceptionally fine grained rocks previously were considered seals for conventional sandstone or carbonate reservoirs rather than reservoirs themselves. Therefore, mudrock was not intensely studied. It was almost enough to know that they were impermeable. Mudrock research now mandates describing compositional stratification and repetitive patterns (cycles) that generally are present. Mudrocks, because of their fine-grained character, are notoriously difficult to describe visually in a way that enables sufficient recognition of stratigraphic variation. Although mineralogical and organic carbon analyses are helpful, costs of analyses are often prohibitive. One promising approach is using geochemical characterization whereby elemental compositions are quantified rapidly by X-ray fluorescence scanning (XRF). XRF allows hundreds of sample locations to be analyzed for the cost incurred by analysis of one sample by X-ray diffraction (XRD) and organic carbon (TOC/RockEval) analyses. Through deduction facilitated by the development of a limited number of mineralogical analyses (by XRD), elemental data can be interpreted to provide the probable mineralogical variation of rock. From these data, interpretation of mineralogical variations in a stratigraphic succession (usually in oil-field



Mixing between younger and older groundwater allows discovery of preferred recharge areas with use of Mg/Ca values.

cores) can be provided. Elemental and inexpensive isotopic data also inspire insights into the variation of ocean chemistry during sediment deposition. Such insights enable interpretations

of the geographic scope of environmental conditions that may or may not have been conducive to preservation of organic material that generated hydrocarbons under the influence of geothermal heat while deeply buried. Ultimately, tying stratigraphic compositional information to geophysical well logs is a practical goal in this research because well logs are the primary tools used by industry to develop stratigraphic models for hydrocarbon provinces.

Water, even more than oil and gas, is an irreplaceable resource, without which there would simply be no life on Earth. Development and interpretation of hydrochemical and isotopic data to interpret recharge and flow of groundwater through aquifers are also important aspects of my research. Discovery of relationships between groundwater age (with radioactive isotopes) and chemical composition, which is based on investigations of the Edwards Plateau in west Texas, is enabling identification of locations for aquifer recharge in limestone and dolostone. This approach has the further potential of enabling groundwater districts to recommend pumping rates for stakeholders such that aquifers are not depleted. Similar tools for evaluation of recharge to other types of aquifers are also being evaluated.

The Hole Truth

Dr. Robert M. Reed

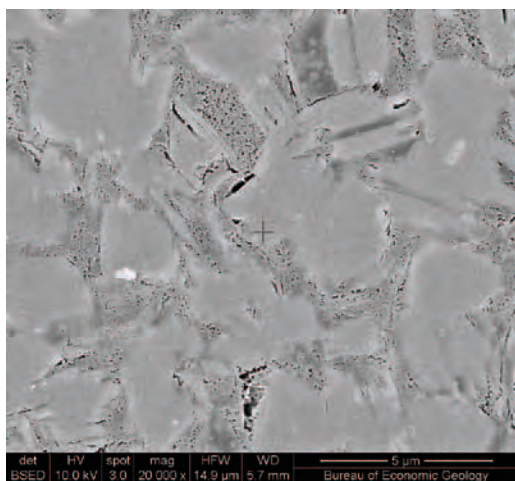


Hydrocarbon production from organic-rich shale is an important part of the world's energy picture, both now and in the future. Understanding how hydrocarbons (both oil and natural gas) are stored in these rocks is an integral piece of the process of harnessing their vast potential. Researchers at the Bureau pioneered work on very small (nanometer-scale) pores in shale. Previously it was thought that very tiny fractures were responsible for much of the storage capacity of shale. Our research has shown this theory not to be the case. Using a sample-preparation technique originally developed for the semiconductor industry, we produced flat surfaces relatively free of unwanted artifacts on shale samples. Observations were then made of the milled surfaces using a powerful field-emission scanning electron microscope (SEM) capable of nanometer-scale resolution. Tiny holes or pores in shale were easily visible using this method. In many samples, pores unexpectedly were present in organic matter, probably owing to formation during burial heating of the rock. Other pores

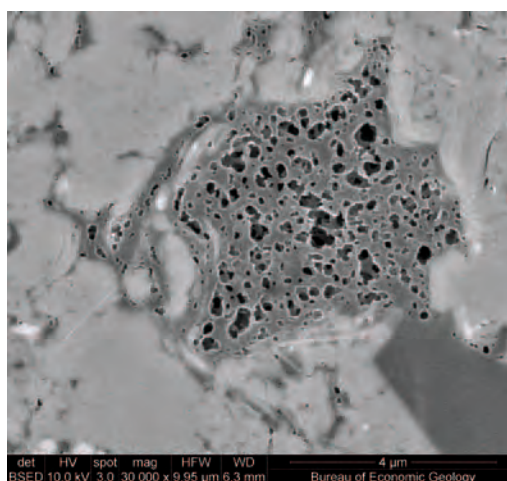
are present between particles or inside particles. Current research involving more imaging focuses on whether all of these pores form a network capable of transferring hydrocarbons within the rock.

Knowing the mineralogy of the particles in shale helps us move toward an understanding of the pores. Characteristic X-ray response of the various minerals allows us to work out their elemental compositions. SEM imaging also provides ground truth to various petrophysical methods that provide estimates of pore shape and size.

I work on shale samples from around the world, but my primary research focus is on material from within the state of Texas. Fortunately Texas abounds in organic-rich shale suitable for my studies. The primary source of material for study is from the Bureau's world-class well-core library. Sample acquisition is augmented by material donations from research-sponsoring companies.



Scanning electron microscope image of organic matter (darker areas) intermixed with the clay mineral kaolinite in a shale. Numerous small pores are heterogeneously developed in the organic matter. Sample is from the Cretaceous Eagle Ford Shale, Zavala County, Maverick Basin, south Texas.



Scanning electron microscope image of organic-matter grain (darker material) in a shale. Interconnected pores are developed in the organic matter. Sample is from the Mississippian Barnett Shale, Wise County, Fort Worth Basin, north Texas.

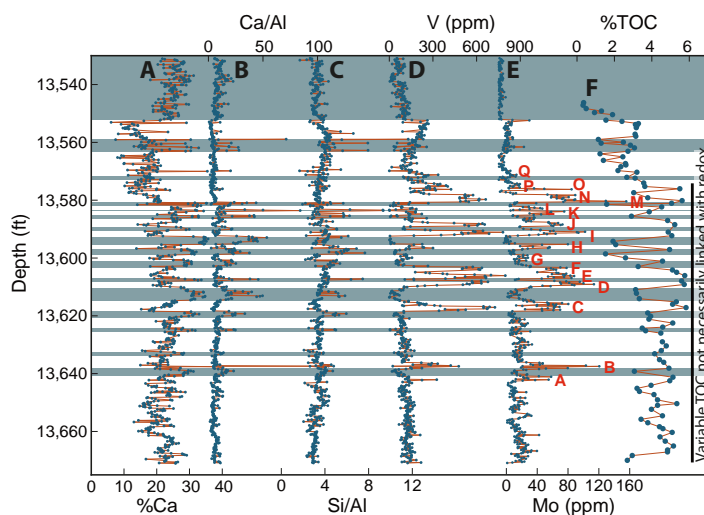


Ocean History 101

Dr. Harry Rowe

The modern ocean is a vast realm of geological and biological activity that we can explore and measure directly—its bathymetry, volume, temperature, salinity, chemistry, circulation, life forms—everything. Unfortunately, past oceans and their properties can be observed and inferred only *indirectly*. Scientists attempt to reconstruct past ocean depths, physical and chemical parameters, and biological activity by studying the sedimentary remains that were deposited on the ancient seafloor. How has this enormous mass of liquid that envelops 70 percent of the modern planet changed over time, and why has it changed? What are the mechanisms that controlled paleoceanographic conditions, and how did past oceans influence the climate and biology of the planet? These are the types of questions that a paleoceanographer like me might ponder and attempt to answer.

Of particular interest to some paleoceanographers are the timing, duration, extent, and cause of ocean anoxic episodes, that is, periods during which oxygen in the ocean is utilized by biological activity but is not replenished. In fact, most of the



Chemostratigraphy for Cenomanian-age strata, Shell Oil Co. J.A. Leppard, #1, Bee County. (A) Stratigraphic changes in %Ca are directly relatable to changes in the limestone (calcite) content of the core. (B) The Ca:Al ratio is a proxy for the calcite:clay ratio of the strata. (C) The Si:Al ratio is a proxy for the quartz:clay ratio and demonstrates the overall low quartz content of the unit. (D) Redox-sensitive vanadium (V) indicates punctuated episodes with reduced oxygen content throughout the middle of the record. (E) Abrupt and cyclical shifts in the stratigraphic record of molybdenum (Mo) indicate rapid and oscillatory changes in the euxinic nature of bottom-water conditions during deposition. (F) Stratigraphic changes in total organic carbon (TOC) reflect preservation of organic matter under variable paleoceanographic conditions.

five major mass extinctions that have transpired since multicellular life began have coincided with episodes of ocean anoxia. What were the conditions surrounding these prolonged or punctuated episodes of anoxia, and why did they occur in the first place?

At the Bureau, I work within a group of sedimentologists and stratigraphers who are documenting the paleoceanographic conditions that prevailed during deposition of a wide range of Paleozoic- and Mesozoic-aged

mudrocks and limestones. Specifically we are demonstrating the intimate linkages between the visual and geochemical characteristics of rock strata. We use a variety of techniques, including X-ray fluorescence spectrometry, X-ray diffraction, and elemental and stable isotope geochemistry of carbon and nitrogen of organic matter and carbon and oxygen of sedimentary carbonates. If the results and interpretations from these successions of marine strata can be integrated with other datasets from around the world, then a more complete picture of how ocean anoxia develops will emerge.

Microscopy at the Bureau

Patrick Smith



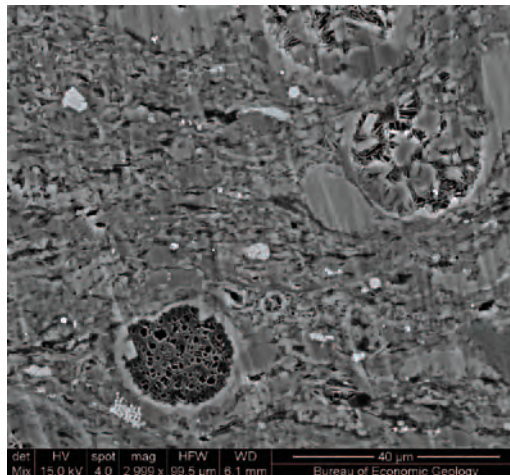
Every time I turn on an electron microscope I know that I am viewing something that has never been seen before. What a kick it is to know that you are part of an original discovery! Very few professionals can make that statement. As luck would have it, I work in a place that gives me that opportunity every day. As a microscopist, I look at things that are very small and help relate them to things that we normally see around us. It is, of course, more complex than that, but it is understood that what goes on at the microscopic level is intimately related to processes occurring on the macro level.

As the Bureau's Electron Micro-Beam Facility Manager, it is my pleasure to provide technical support to our consortium researchers and to serve as a learning center for staff and students at the Bureau. I particularly enjoy participating in collaborative research with academic, industrial, and staff stakeholders. It is exciting to be a part of a team using the scientific process to search for clues to complex questions.

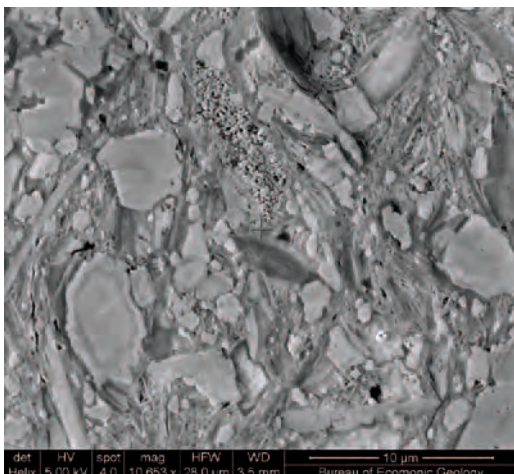
The lab, located in Bldg. 131 (the building across the street from the main building and where the Core Research Center can be found), room 1.210 A & B, is equipped with two scanning electron microscopes. The principal instrument is the FIE Nova NanoSEM Variable Pressure Field Emission Filament instrument, which can provide energy dispersive spectroscopy (EDS),

cathodoluminescence (CL) imaging, and the standard secondary, backscatter micro- to nanoscale imaging. In addition, we have a Philips LX30 Tungsten Filament Model, which is dedicated to creating automated CL-image montages.

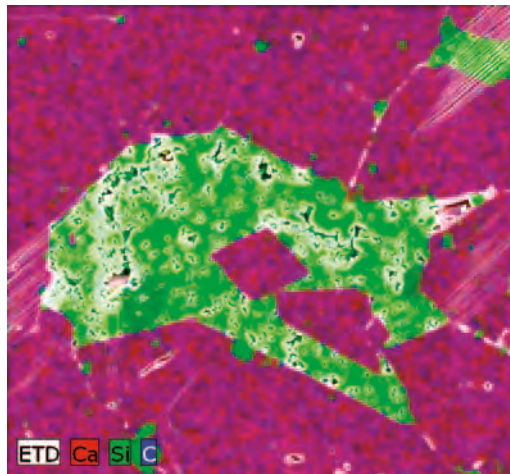
A current major research focus deals with the imaging of unconventional reservoir rocks, mainly tight-gas sandstones, oil shales, and gas shales. However, our technical staff is available to prepare samples, conduct analyses, and to provide training and consultation on any developing interests of our stakeholder team members.



Oil/gas-shale image at 3Kx.



Uncoated gas/oil-shale imaged in low-vacuum mode.



Bitumen sample imaged in EDS map mode.

Geochemical Fingerprints for Oil and Gas Formation and Storage in Organic-Rich Shales



Dr. Tongwei Zhang

Petroleum and natural gas are vital sources of energy. These substances are formed by the transformation of organic matter through biogeochemical processes and thermal degradation within source rocks. Oil and natural

gas are generated and then migrate out of the source rock, or “kitchen,” along faults or fractures. The oil and gas may then accumulate in permeable sandstones or fractured carbonates, or they can be stored in pores within the source rocks. An observable difference can be found in API gravity, oil waxiness, and gas wetness of migrated oil and natural gas as compared

with hydrocarbons that are stored in situ. This difference is due to the preferential migration of lighter hydrocarbons. Biomarkers such as gas isotopes can be used as geochemical fingerprints to indicate the source of oil and gas—depositional environment, source-rock type, thermal maturation level, migration paths, and secondary alteration (biodegradation and oxidation).

The Bureau’s new Gas Geochemistry Laboratory on the J. J. Pickle Research Campus has been developed to study hydrocarbon chemistry and source-rock properties. The lab’s capabilities include identification and quantification of 18 gas components; oil extraction from organic-rich shales; liquid hydrocarbon identification and quantification with GCMS; analysis of source rocks, including surface area, pore volume, and pore-size distribution; and high-temperature/pressure rock-brine interaction experiments. The laboratory equipment includes a custom-built high-pressure pure gas adsorption/desorption system, an Agilent 7890A gas chromatograph, a custom rock-crusher

sample cell and Spex sample prep 800M mixer/mill for use with GC system, a Shimadzu GCMS-QP2010S gas chromatograph/mass spectrometer, a Foss Soxtec 2043 extraction unit, and a Quantachrome Autosorb iQ-MP physisorption analyzer capable

of monitoring pores from 0.35 to 300 nm in diameter. These instruments allow detailed characterization of gas and liquid hydro-carbons and of source-rock pores.

Recent Bureau work has focused on the study of oil-storage mechanisms and oil saturation in the Bakken and Eagle Ford Formations. The conventional model for determining petroleum

expulsion efficiency is based solely on petroleum generation and needs to be revised by combining hydrocarbon generation, pore characterization, and mineralogical/lithological characterization of organic-rich source rocks. Our preliminary results show that lithological stacking patterns greatly affect petroleum expulsion efficiency (PEE). Differences in PEE can be quantified by analyzing the chemistry of gases released from source rocks and by analyzing the chemistry of the residual oil. Newly developed pore-size-distribution techniques allow oil saturation to be determined within organic-rich shales. Oil saturation is an important parameter used to determine hydrocarbon migration mass-balance calculations. The process of oil migration and expulsion in the organic-rich shales is much more complicated than previously expected, and an intensive integration of geochemistry, geology, and pore characterization is needed. My newly developed laboratory is uniquely suited to this new and important field of research.

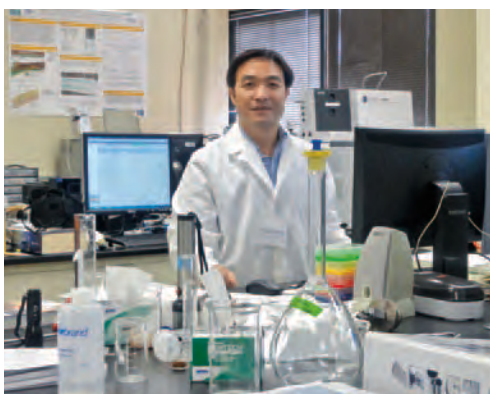


Photo courtesy of Yanyu Wang

Submarine Slides, Tsunamis, and Martian Oceans!

Dr. Lorena Moscardelli



In 1929 the Grand Banks earthquake triggered a submarine landslide that generated a tsunami that killed 27 people along the Newfoundland coast. A similar event in Papua New Guinea killed 2,200 people in 1998. In 2006, the Luzon Strait submarine landslide caused the massive failure of undersea cables, interrupting the internet between Taiwan, Vietnam,

South Korea, and Singapore and causing millions of dollars in losses. All these events have made us realize that the seafloor is a dynamic environment with the potential to do harm. The Society for Underwater Technology estimates that the cost of damage to pipelines caused by submarine landslides is on the order of \$400 million a year. Ancient submarine landslides can also play an important role as seals for hydrocarbon reservoirs in the subsurface, as well as in shaping the architecture of continental margins around the world. I am a Research Associate and the co-Principal Investigator of the Quantitative Clastic Laboratory (QCL) consortium at the Bureau, and I have been studying submarine landslides and all things mass wasted since 2003. However, my research interests span a range of topics, including utilization of large, industry-acquired, basinwide, 3D seismic datasets, and accompanying 2D seismic, well log, core, and other pertinent geological and engineering datasets to help me understand how continental margins evolve and how sediments and structure interact in these geologic settings. I am also interested in the application of quantitative seismic geomorphology techniques for characterizing oil and gas reservoirs and for



Looking at some rocks in the San Rafael Swell, Utah—an anticline formed during the Laramide Orogeny.

resource assessment and extraction.

My interest in submarine landslides has taken some of my research to unconventional and intriguing places! Last year, I suggested that triangular geomorphological features located in the downstream end of outflow channels on Mars (tear-drop-shaped islands) are consistent with the formation of channels debouching

debris flows on the peripheries of an ancient ocean that once occupied the Northern Plains of Mars. I made the suggestion on the basis of striking similarities between these tear-drop-shaped islands on the red planet and similar triangular elements that I previously described in the deep-water region of offshore Trinidad (erosional shadow remnants) and that form part of a 2000-km² submarine landslide. I have also suggested that large-scale polygonal terrains on Mars are analogous to deep-water polygonal fault systems on Earth—an observation that also supports the existence of an ancient ocean on Mars. My long-term Earthly mission, however, is to pursue detailed seismic geomorphological studies on continental margins around the world to characterize shelf-margin evolution and architecture through time. In order to accomplish this mission, I work closely with students that are currently pursuing research on a variety of continental margins around the world, including offshore Norway, Trinidad, New Zealand, and the Gulf of Mexico. I am an active member of the Graduate Studies Committee at the Jackson School of Geosciences, and I also teach a graduate-level class on subsurface mapping and petroleum workstations.



The Rock Doctor is in!

Dr. Lesli Wood

Rocks and sound are two things that naturally go together. Both inform my life. I am a geoscientist and a teacher. I am a musician and a songwriter. Whether I am in the field working in some spectacular natural setting that lends itself to writing a new song or interpreting seismic data where rocks interact with sound to produce spectacular results, I am engaged in the study of both rocks and sound.

I am co-Principal Investigator of one of the Bureau's Industrial Associates programs, the Quantitative Clastics Laboratory (QCL), and we interpret many ancient landscapes and seascapes in seismic data. Today seismic data—basically images of Earth's interior from a response of artificially generated sound waves interacting with rocks beneath the surface—can image land forms and provide a window into ancient worlds as never before. These data can be used in explaining the depositional systems active millions of years ago, collecting data on producing hydrocarbon reservoirs that allow us to model their extent and character beyond the reaches of our data, and enabling us to examine how ancient Earth's rivers, deltas, and oceans responded to climate, tectonics, and sea-level changes. When combined with details provided by outcrop study of similar rocks, these data help us build a rock pore-to-basin-scale picture of what ancient systems looked like and



Teaching GeoFORCE 10th graders, Grand Canyon.

how modern systems might respond to future changes on Earth. QCL and our student researchers work from northern Alaska to the basins of New Zealand and all parts in between, supported by funds from hydrocarbon companies who thirst for new ideas and new ways to better explain and safely explore their clastic reservoirs.

Photo courtesy of Dequ Ratchiff

The opportunity to see so much of the Earth, travel to so many cool places, and meet so many fascinating people naturally provides a lot of material for my songwriting side and a lot of opportunity to create music. I grew up running in the hills of the Arkoma Basin of central Arkansas. My parents took us camping and traveling coast to coast and backpacking through the Rocky Mountains. Today I blend my science with my music by writing about places I have been and people I have met, enjoying playing music with the many geoscientists worldwide who double as musicians. My albums have songs on them inspired by travels in Azerbaijan, the Caribbean, India, the Rocky Mountains, and many of Earth's hidden geologic gems. I find music a great way to meet people and inspire people to look at the world in unique ways. This perspective transfers to my teaching in industry, the university, and in our JSG GeoFORCE program. If I can get students to find their own inner "Rock Doctor," then I have done my job.

"Old stones, fallen timbers
Morning paths that fade with time.
Leaved branches, over memories
Lift them back to see what's mine."

- *Old Stones* (from the album *Child of the Water*, copyright 1999 L. Wood)

A Story in Seismic

Dallas B. Dunlap

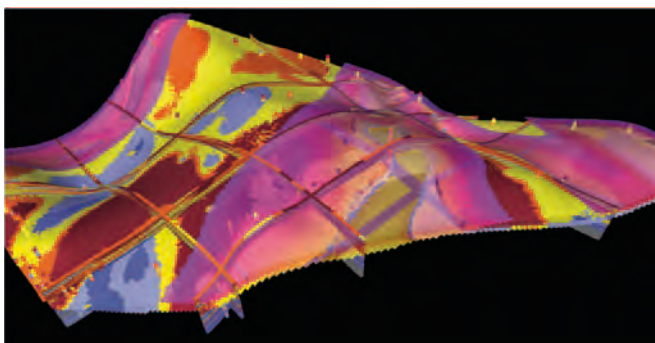


The teacher tells the enthusiastic group of third graders to settle down as she goes to turn up the lights at a Killeen ISD Career Fair. The students, recently enthralled by 3D visualizations of central Texas aquifers, Martian volcanoes, and the idea of lasers shooting from airplanes to measure beach erosion, are eager to learn more. So after completing the presentation, I begin with a simple question: “What do geologists do?” A brown-haired boy to my left answers, “You study rocks,” another says, “Look for dinosaur bones.” I reply with, “Well, yes, but more than that—geologists are storytellers.”

The job of a geologist is to look at collections of data from multiple sources and develop a story about how Earth and the environment evolved over time to result in the planet we live on today. In many cases, the person studying that rock sample, fossil, or outcrop might be the first one ever to look at and document it—and the first to tell the story of how that unique object formed.

As a researcher in the Quantitative Clastics Laboratory at the Bureau, I’m always struck by that thought as I analyze new seismic data for the first time from far-off lands. Seismic data give us the ability to view large areas of Earth’s subsurface with an increasing clarity and acuity. High-resolution 3D datasets compiled from acoustic-wave reflections mimic the layered structure found below Earth’s surface thousands of square kilometers across and

several kilometers deep. And now, new computing technology is enabling us to visualize these large datasets like never before, giving us a remarkably detailed view into the past.



Reservoir model of tidal-bar sands and an incised valley from the Cretaceous western interior. Sizes and shapes of sand bodies were predicted from a knowledge base built from seismic data, lidar, and field observations.

In my job, I mark and interpret many layers in the seismic data and correlate the depth below the surface to a time in Earth’s distant history. Once I’m finished, we can use this framework of timelines and surfaces to constrain the age of events between the layers. The varying brightness of these seismic data

reflections within the layers is also an indication of the paleo-environment, and it records changes in lithology or porosity in the rock. We can use the shape and size of these “bright spots” to describe what was happening on Earth’s surface during that time. Possible examples, such as buried channels, dunes, or tidal bars, are preserved as seismic anomalies in the dataset. By stacking these multiple layers with interpretations of the progression of anomalies, we can describe how a field or basin evolved over geologic time. Energy companies can further utilize this information in complex reservoir models to predict the distribution and shape of hydrocarbon-bearing sands so that fields can be developed and drilling locations can be more accurately targeted. In the end, I become that storyteller that I described for the third-graders, while at the same time helping others to search for needed sources of energy in Texas.



From Outcrop to Environment: Imaging and Interpreting Earth's History

Dr. Peter Flaig

As a kid growing up in Wisconsin, I was always fascinated when I found a fossilized sea critter in my neighborhood particularly because I lived thousands of miles away from the ocean. How did this animal that obviously belonged in an ocean end up in the Midwest inside a rock? This fascination ultimately drove me to geology and investigation of ancient environments: I am a clastic sedimentologist. My interest lies in reconstructing ancient environments by looking at sediments, primarily those deposited in ancient rivers, on floodplains, on deltas, and in environments near and in the shallow ocean.

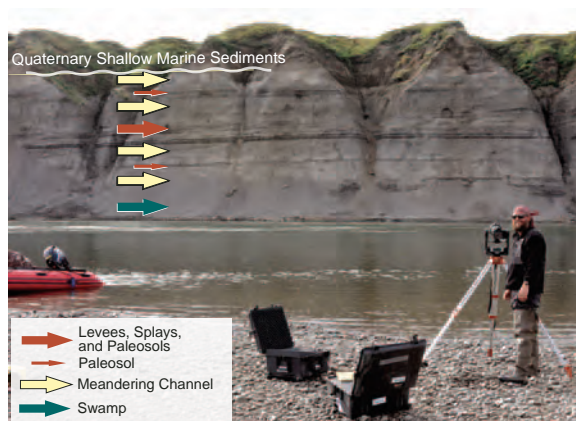
My research focuses on large outcrop belts in Arctic Alaska, the western United States, and Antarctica. Large outcrops are unique because they provide an accessible, laterally extensive, and sometimes three-dimensional view of a slice of Earth. Each layer records an environment or event, and together they preserve a record of environmental change over time. Not only am I interested in how deposits and environments change, but I also use sedimentology to determine how forces such as mountain building, erosion, sea-level fluctuations, and climate change help drive and preserve these changes. In my research I systematically record facies (rock type), fossils, critter tracks and trails, rock properties, stratal geometries, and patterns of sediment deposition. By following this approach, I can produce a paleoenvironmental reconstruction for a given location, which can be incorporated into other scientists' research (paleontologists, biologists, climatologists) for modeling their systems. These reconstructions provide critical

information to industry. Outcrop exposures not only allow us to reconstruct Earth history, but

they also hint at what lies beneath us, beyond our view. Many of the sediments that I study form extensive oil and gas reservoirs or regional aquifers, and outcrops provide tangible analogs. I think that the more geologists do to help document these systems, the more accurate both climate modelers and those who extract critical resources can be.

Before I became a geologist, I was a

professional photographer. Photography and sedimentology complement one another because the uppermost layers of Earth are extremely complex. One of the best ways to accurately record the interplay between sedimentary structures, facies, and outcrop architectures is through detailed photography. Photography and other imaging techniques such as lidar (light detection and ranging), coupled with process sedimentology, allow me to "bring the outcrop home with me." I find this ability advantageous and often necessary because my research has taken me to many difficult-to-access places. Because I know ancient, high-latitude systems can provide critical deep-time climate data, I spent 10 field seasons on the North Slope of Alaska studying near-polar Cretaceous ecosystems and two Austral summers in the Central Transantarctic Mountains of Antarctica examining sedimentation across the Permian-Triassic extinction event. I continue this work while expanding research into fluvial-delta deposits (reservoir analogs) of the Western Cretaceous Interior Seaway in the west-central United States. In the near future I hope to involve Jackson School graduate students in my research.



Northern Alaska Cretaceous Prince Creek Formation outcrop.
Note imaging equipment and paleoenvironmental interpretations.

Photo courtesy of Stephen Hainolis

Research into the Smallest, Largest, and Deepest Pores in Hydrocarbon Reservoirs

Dr. Bob Loucks



I am a Senior Research Scientist involved in several research projects spanning sequence stratigraphy to pore networks in carbonates, mudrocks, and siliciclastics. As co-PI of the Carbonate Reservoir

Characterization Research Laboratory (RCRL), I work on the origin and distribution of microporous reservoirs (tight carbonates) and carbonate and evaporite paleokarst. In my research on micropores, I image pores in the range of 40 nanometers to several microns, and my work will help in the understanding of how to drill worldwide for oil and gas in these tight, unconventional, carbonate systems.

My work on karst has defined the stages of how cave systems form in carbonates and evaporites, as well as how they evolve with burial. As cave systems become buried and collapse, large breccia zones develop, not only in the cave-system interval, but also in the strata above the cave zone. These large, brecciated, and collapsed damage zones form hydrocarbon reservoirs, such as the Lower Ordovician Ellenburger Group in west Texas.

As co-PI of the Deep Shelf Gas Project, I have as my major goal to explain how pores evolve in Mesozoic and Tertiary sandstone with depth in the Gulf of Mexico. This is important research because it helps oil companies understand the risk in finding hydrocarbons in the deep and very hot sediments buried more than 25,000 ft in high-operating-cost offshore areas.

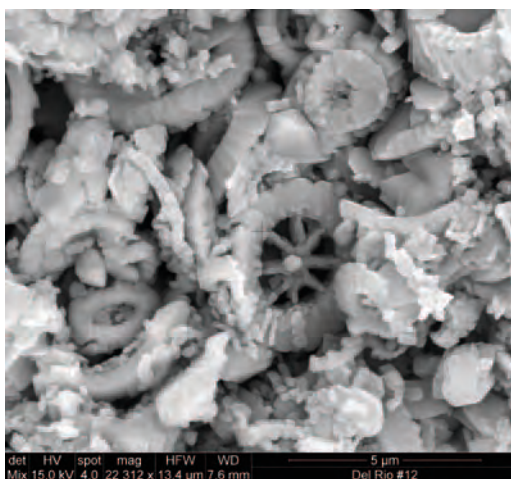
As co-PI of a project for a major oil company, I am involved in examining pore networks in deeply buried carbonate strata in the Gulf of Mexico. Understanding the type and number of

pores present in these carbonates is crucial to exploration programs designed to successfully drill economic reserves. Estimating the types and numbers of pores in different carbonate rocks decreases the risk for oil companies' drilling of dry holes.

I am also an active researcher in unconventional-shale systems and am actively investigating the pore types and pore networks within siliciclastic and carbonate mudrocks. The pores in these rocks range from less than 5 nanometers up to 1 micron. My co-

researchers and I were the first to recognize organic-matter pores in the Barnett Shale and develop the argon-ion-milling method to study these pores using a scanning electron microscope. This research group has now studied pore networks in many more mudrock systems and summarized their results in a publication that covers the spectrum of mudrock pores, as well as a working classification of these pore types.

Finally, I work as a consultant on the STARR (State of Texas Advanced Reservoir Recovery) program. This is a program that helps companies enhance their exploration and production by applying cutting-edge geologic tools and concepts to their operations.



Example of micropores in Buda chalk. Grains are coccoliths, which are algae that live in shallow waters of the deep sea.



From Mountaintop to Subsurface: Understanding Carbonate Rocks in 3D

Dr. Xavier Janson

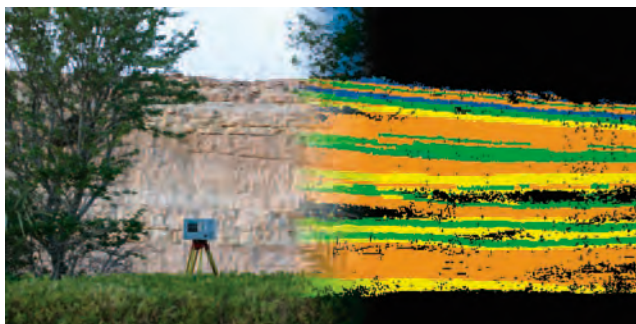
More than 60 percent of world oil and 40 percent of gas are held in carbonate rocks. However, carbonate reservoirs are usually considered heterogeneous and complex by geoscientists.

Typically our knowledge of subsurface rock comes from either geophysical methods (seismic data) or direct observation of rock cores. 3D seismic data provide continuous subsurface coverage (especially rock layers), but they show only a difference in acoustic properties of these rocks, not the nature of the rocks or their reservoir properties. In addition, the seismic resolution is typically lower than what geologists like for a comprehensive understanding of the reservoir. It is like looking at a landscape with fogged glasses—a general sense is there but without the details for a full appreciation of the beauty.

Similarly, analyzing rock from core gives geologists a true picture of the reservoir and its subsurface geology with as much detail as can be extracted from the rock. However, this information is valid only for the small volume of rock present in a 4-inch-diameter core.

Most hydrocarbon fields have a well spacing of roughly 300 m and reservoirs that are a few hundred feet thick. Geologists then only know what the rock looks like in a small fraction of the total reservoir volume (typically less than 0.01%).

Most petroleum geologists wish they could see and touch the reservoir. One way to do so is to find a rock equivalent to that of the reservoir that has



been brought to the surface by tectonic processes and now crops out at the surface. On certain mountains and cliffs the reservoir rock can be observed as a whole or in detail. How the rock layers are organized can be seen, along with the lateral variability of

the layer geometry and the type of rock or reservoir properties in the layers. This information can then be taken back to the lab, and it can be modeled in 3D to resemble the subsurface of the reservoir. Seismic, too, can be modeled to fit the outcrop just seen in the field.

Thus, if the knowledge gained from observation of the carbonate rock in the outcrop is combined with the study of the subsurface dataset, the huge volume that little is known about between the wells can be better predicted.

The preceding is just a taste of what we do at the Reservoir Characterization Research Laboratory (RCRL). In 2002, I joined this group of researchers who use outcrops from all over the world and subsurface geologic and geophysical data from carbonate reservoir strata in the development of new and integrated methodologies for a better understanding and description of the 3D reservoir environment in the subsurface. My research has focused on how to (1) integrate traditional field methods and new technology such as lidar scanning of outcrops so as to have a detailed 3D image of the outcrops we study and (2) build accurate, realistic 3D geological and geophysical models and apply this knowledge to real subsurface reservoirs.

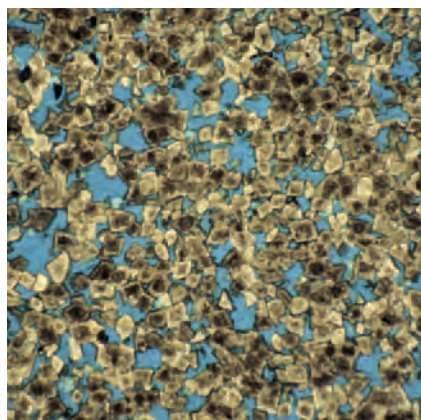
Pore Space Makes Carbonate Petroleum Reservoirs Perform Magnificently

F. Jerry Lucia

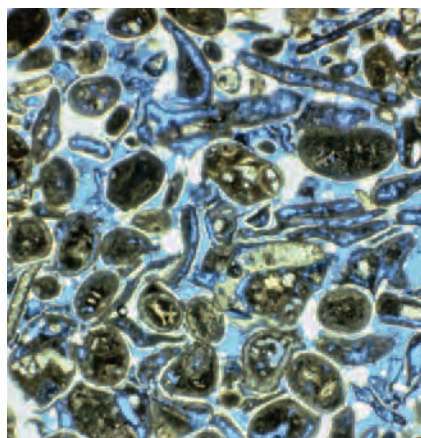


Half of the world's oil and gas production comes from subsurface reservoirs composed of the carbonate minerals calcite (CaCO_3) and dolomite ($\text{CaMg}(\text{CO}_3)_2$). The economics of such petroleum production is related to the volume of petroleum and the rate at which it can be produced. Some of the largest reservoirs in the world are found in carbonate rocks. Although some of these reservoirs produce at prolific rates, some need expensive enhancements to recover any oil at all. In general, the difference in production rates is related to the nature of the petroleum and to the type of pore space found in the reservoir. Flow rates are related directly to a rock property termed *permeability*, the most economical reservoirs having the highest permeability and the highest flow rates. As a rock property, permeability is a function of the size and distribution of pore space—*pore-size distribution*. In

carbonate reservoirs, pore space is found in many different forms and in various locations, such as between depositional grains and carbonate mud-size particles. In addition, pore space of various sizes is found within carbonate grains. Pore-size distribution is complicated by changes that occur after carbonate deposition—*diagenesis*. Pore size may be reduced by pore-filling carbonate cement, and large pores may be formed within grains by carbonate dissolution. A unique diagenetic change is the conversion of calcite to dolomite—



Blue = pore space between carbonate grains.



Blue = pore space between dolomite crystals.

dolomitization—the conversion of limestone to dolostone. Dolomitization can change pore-size distribution dramatically from small pores in limestone to large pores in dolostone. As a result, many of the best carbonate reservoirs in the world are dolostone reservoirs. In addition, fracturing and dissolution can form a pore system that is unrelated to either deposition or dolomitization. Most caves around the world are found in carbonate rocks, and for many years carbonate reservoirs were thought to produce from paleocave systems—often referred to as *karsted reservoirs*. Indeed, some of the most productive carbonate reservoirs produce from a complex pore system composed of cavernous pore space, fracture pore space, and limestone or dolostone pore systems.

My principal interest is studying the origin and distribution of carbonate pore space. I am co-founder of the Carbonate Reservoir

Characterization Research Laboratory (RCRL) at the Bureau and have studied carbonate reservoirs in the United States, the Middle East, and Canada. My goal is to integrate petrophysical properties of carbonates into depositional and diagenetic models through gaining an understanding of the origin of rock fabrics. I work with carbonate sedimentologists, geochemists, reservoir engineers, and computer-modeling experts to accomplish this goal.

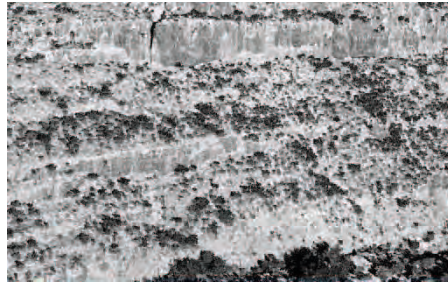


Geospatial Science

Logan Pennington

Geospatial science encompasses multiple sciences and ways of life, so what would the Bureau's Reservoir Characterization Research Laboratory (RCRL) use it for? RCRL uses several forms of geospatial science to analyze carbonates and other geological features. Lidar (light detection and ranging) is a powerful, evolving form of geospatial science, and orthogrammetry (use of geo-referenced photographs) has become popular in recent years. But lidar sensors for scanning geological features at long range can be first credited to Dr. Charles Kerans. In geology, scanning a targeted outcrop creates a 3D image for mapping and engineering software use in mapping of features that would normally take days or weeks to map using other methods. The resulting image comprises millions if not billions of tiny points similar to pixels in high-resolution photographs. These points are what the sensor receives from an object after the laser is fired. How powerful the sensor is and the distance from the target can determine the amount of detail achieved. Once the outcrop is scanned, the data can then be calibrated (geo-referenced into the proper coordinate system), and all data are merged into one large 3D image. At this point, high-resolution photos can be draped over the lidar to add real-world color to the image. A high-quality photograph matching the resolution of the lidar makes data more effective for interpreting real-world features.

How do we acquire lidar and orthogrammetry anyway? Currently RCRL owns several Optech ILRIS lidar laser scanners—stationary sensors mounted on tripods and aimed at a targeted area. Powerful cameras can be mounted atop the lidar sensors, along with a gigapan—a small robotic device that moves the camera so that highly accurate overlapping photographs are taken. New software, Quick Terrain Modeler, allows the merging of high-resolution photographs and high-point-density lidar to be simplified, although certain constraints are required for accurate interpretation of colored geological features. First, the lidar system must not be farther away from the desired target than 3,000 m; otherwise, data holes will occur in the image. Second, the lidar system must be a minimum of 3 m away from



Photos courtesy of Chris Zahm

Examples of intensity lidar and colorized lidar, Walnut Canyon, Guadalupe National Forest, NM. Photos by Chris Zahm and Logan Pennington.

the target, although generally the closer to the feature the system is, the more detail is detected. Third and most important for the fusion of lidar and imagery is that the gigapan photograph must be taken from the exact same position as that from which the lidar is shot so that the angles of the lidar and image match, representing the most accurate 3D model. New acquisition methods and new analytical software were discovered in 2012, too, and new technology such as aerial drones and hyperspectral cameras are being evaluated as viable tools in the ever-evolving realm of geological research.

the target, although generally the closer to the feature the system is, the more detail is detected. Third and most important for the fusion of lidar and imagery is that the gigapan photograph must be taken from the exact same position as that from which the lidar is shot so that the angles of the lidar and image match, representing the most accurate 3D model. New acquisition methods and new analytical software were discovered in 2012, too, and new technology such as aerial drones and hyperspectral cameras are being evaluated as viable tools in the ever-evolving realm of geological research.

the target, although generally the closer to the feature the system is, the more detail is detected. Third and most important for the fusion of lidar and imagery is that the gigapan photograph must be taken from the exact same position as that from which the lidar is shot so that the angles of the lidar and image match, representing the most accurate 3D model. New acquisition methods and new analytical software were discovered in 2012, too, and new technology such as aerial drones and hyperspectral cameras are being evaluated as viable tools in the ever-evolving realm of geological research.

What Does Your Fracture Map Look Like?

Dr. Chris Zahm



Imagine an underground irrigation system that runs in reverse. Water droplets on the grass are lifted into the air and flow toward a sprinkler head, changing from mist to a stream of water. Once inside the sprinkler, the water begins to flow along a series of underground pipes that become progressively larger as they approach the source of the water. Now imagine you want to capture some of this water for your own use. One the

most useful items for tapping into this water supply would be a map of the underground pipe network. In studying fractured reservoirs, one of the primary goals is to understand how the “pipes,” or fractures, are distributed in the subsurface. Reservoirs are hundreds or thousands of feet underground, making it extremely difficult for geologists to map fracture systems, which are significant distribution pathways for hydrocarbons. As a result, in order to create a 3D model, we have to look at analogs to study the likelihood of fractures developing in certain types of rocks. These analogs include known reservoirs and outcrops; however, the ultimate goal is to actually map the reservoir “pipes.” The Reservoir Characterization Research Laboratory (RCRL) group at the Bureau has been studying carbonate systems for 25 years in hopes of mapping permeability pathways in subsurface reservoirs. Over the course of many characterization projects, we have discovered that carbonate rocks—predominately limestone and

dolomite—are susceptible to fracturing under natural conditions. However, not every carbonate develops the same style of fractures, and the

size of the fractures varies significantly, depending on what process (such as faulting or folding) breaks the rocks. All of these factors must be considered when fracture systems are characterized.

As part of the RCRL consortium, I work to build better fractured-reservoir models. I use

concepts of structural geology and stratigraphy to distribute fractures in the subsurface so that the members of my consortium can become better predictors about fractures in their own subsurface reservoirs. I have worked on reservoirs around the world, but our current research initiative in the Guadalupe Mountains has implications for reservoirs in the Pri-Caspian, Permian Basin, and Cretaceous Gulf of Mexico. Other work along the Pecos River in south Texas has been used as an analog for carbonate fractured reservoirs in the Campos Basin of Brazil and in the Gulf of Mexico. Our group has been examining massive paleokarst collapse in the Texas Hill Country and in Montana and Wyoming as an analog for fracture development in a large, heavy-oil reservoir in western Canada. One of the most spectacular folded carbonate sections from the Wyoming Mississippian Madison Formation was used recently as an analog for a fractured reservoir model in the Middle East.



Forelimb of Sheep Mountain Anticline in Wyoming. Note varied distribution of tall and short fractures (dark lines crossing fold). Many features do not project into younger strata. Understanding size, distribution, and cause of these fractures or “pipes” is the main intent of my research.



The Sea Goes in and the Sea Goes out

Laura Zahm

Central Texas geology is dominated by deposits from a shallow, warm sea that existed during the Early Cretaceous period (approximately 100 million years ago). These deposits are limestone. Throughout geologic time there have been periods when sea level was high, flooding large expanses of the continents, and other periods when sea level was low, exposing the continental shelves and uncovering land bridges between continents. These large fluctuations are generally thought to have been driven by the presence or absence of glaciers on Earth. But during the Early Cretaceous, glaciers were almost

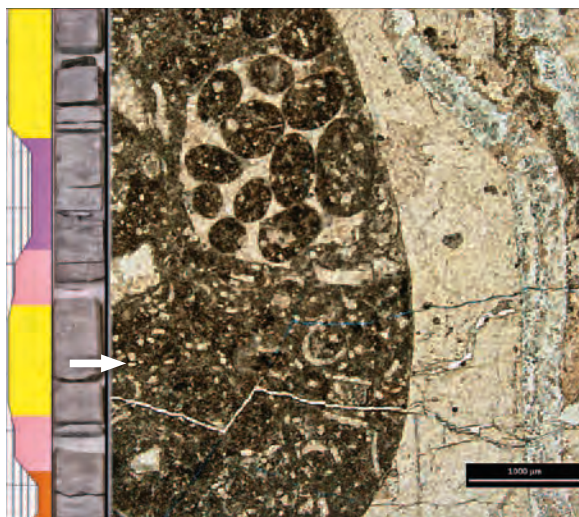
entirely absent on Earth, although there is evidence in the limestone deposits of sea-level fluctuations during this period. For the past 18 years, I, along with fellow carbonate researchers at the Bureau, have examined outcrop and subsurface datasets to decipher sea-level fluctuations in the Cretaceous rock record. The patterns observed in the rock record are broken down into cycles that can be mapped over large areas. The three-dimensional shapes of these formations determine the shape and extent of oil and gas reservoirs. The more accurately we can characterize the depositional environment of the rocks and what changed during their burial, the more efficiently the reservoir can be produced. What we have learned from the

Lower Cretaceous deposits here in Texas can be applied to reservoirs of similar age in the Middle East, South America, and elsewhere.

The focus of my research at the Bureau is utilizing the information preserved in the rocks for a better understanding of reservoirs. By reading the rocks, we can travel back in time. Life in the oceans is recorded in carbonate rocks, including limestone. Each fossilized organism can tell us something about the environment in which it lived: water depth, water chemistry, nutrient levels, wave energy, water clarity, and water temperature. By describing an assemblage of

organisms that lived in

the same place and time and using analogs from organisms alive today, we gain an understanding of that environment millions of years ago. A single core can give us information about several environments, as well as illuminating environmental changes over time. For example, if we see a shift from deeper water organisms to shallower water organisms, the sea level has fallen. By analyzing cores and examining assemblages of organisms under a microscope, we can make paleoenvironmental interpretations, identify sea-level fluctuations, and build a three-dimensional picture of the reservoir.



Color blocks = changes in rock type and fossil assemblage adjacent to photos of core. Horizontal line = 1 ft. Photo = view of rock in thin section at arrow. Large shell fragment filled with dark-brown sediment, algal particles, smaller shell fragments, and ball of peloids held together by cement.

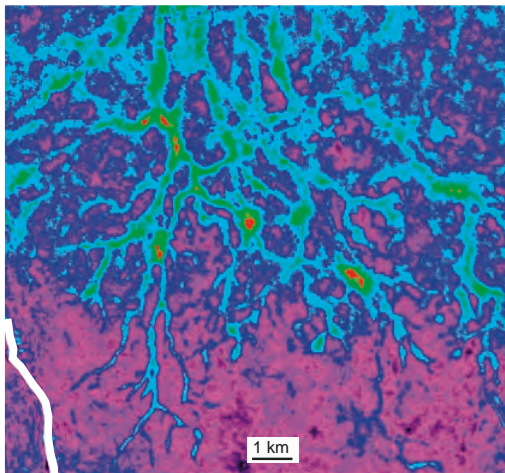
Seismic or Sedimentology?

Dr. Hongliu Zeng



A big challenge for geoscientists is predicting lithology and reservoir geometry in sedimentary basins. Reservoir distribution and quality are important to an understanding of underground water and hydrocarbon resources and to determining effective ways of recovering these resources, especially now as the U.S. strives for energy independence. Yet interpreting these reservoirs without actually seeing them is not easy. Study of sedimentology in modern depositional environments, in outcrop sites, and in core does provide useful models of geologic settings and facies. Prediction of the physical distribution of depositional systems in the subsurface, however, requires geophysical data, especially seismic data.

Historically, seismic interpreters have analyzed seismic volumes for field-scale (50 m or thicker) geologic and depositional features. Sometimes reservoir-scale (1–10 m thick) features can be detected in vertical sections, but many of these small-scale targets cannot be resolved and interpreted because of data-bandwidth limitations. My mission at the Bureau has been investigation of innovative methods for interpreting seismically thin depositional systems routinely and cost effectively for accurate prediction of hydrocarbon reservoirs. Potential breakthroughs may occur from the seamless integration of sedimentology and seismic geophysics.



Seismic-amplitude stratal slice created from 3D seismic volume in Cretaceous Songliao Basin, China. Numerous channel forms reveal a lacustrine shallow-water deltaic system largely composed of distributary-channel facies in the delta plain and delta front (red and green), and muddy sediments in a shallow lake (magenta). According to core description and modern analogs, the system developed on a gentle slope (<math><0.5^\circ</math>) with maximum water depth of <math><10\text{ m}</math>. Measured channel-sandstone thickness 1–9 m in wells.

Combining seismic interpretation of lithology and high-resolution horizontal seismic imaging

of ancient landforms has led to an approach called *seismic sedimentology*—a new field in sedimentology and seismic interpretation. Seismic sedimentology is the use of seismic data in the study of sedimentary rocks and the processes by which they were formed. With current technology, seismic sedimentology is limited to study of seismic lithology and geomorphology, depositional architecture, and depositional history, with seismic lithology and geomorphology composing the backbone of seismic sedimentology. By applying seismic lithology, we can convert a 3D seismic volume into a log-lithology volume. In such a volume, lithology logs (GR and SP) at wells are tied to nearby seismic traces within a

small tolerance, ensuring the best possible well integration with seismic data at the reservoir level. Using seismic geomorphology, we further convert seismic data into depositional-facies images using lithologic identification, which is the basis of high-frequency sequence and systems-tract mapping.

As a Senior Research Scientist at the Bureau, I lead the seismic sedimentology and integrated interpretation program. My research spans the world, including projects from the Gulf of Mexico, west Texas, South America, China, and the Mideast. I won the AAPG Pratt Memorial Award in 2005 for Best Original Article published in the *AAPG Bulletin*.



Herding Cats

Stephaine Lane

Which came first, the line in the 2000 Super Bowl commercial or the phrase “herding cats”? Although the phrase has been around for a while, the image of tough cowboys on horseback attempting to herd cats across a rugged plain certainly was a funny image for us to latch onto back then. But these days, at my job at the Bureau, I have had to face the fact that sometimes humans appear to be being “herded” simply because tools and methods are inefficient. It just seems wrong to say that a group is characteristically unpredictable and untamable—it is, in fact, more likely that the tools and approaches used in helping to guide the group are not effective.

I work for the Reservoir Characterization Resource Laboratory (RCRL), a group of 28 consortium sponsors that I have found to be dynamic individually. I work for five researchers and from four to eight students. One of the things I first noticed about the group and their industry sponsors was the level of energy and enthusiasm in what they do, where they want to go, and their dedication to getting there. But beyond that, they are all individuals with different personalities, ideas, and methodologies in the workplace. In order to successfully coordinate their activities, I have to understand how and under what environments they work best. The better I know my group—their likes and dislikes, their stressors, their priorities and passions, their strengths and weaknesses—the better I can successfully coordinate the group. It is my responsibility to (1) know what each person needs to be successful, (2) how I can help make that a reality, and then (3) integrate it into the group.

My primary purpose is to coordinate with all RCRL sponsors to facilitate the collective end-goal: successful delivery of the newest and most integrated reservoir data to the consortium.



Photo courtesy of Robert Youens.

Most of what I do is administrative and generally is conducted behind the scenes. My responsibilities include coordinating all aspects of our annual meeting and group field trips. I also oversee completion of our sponsors’ contracts and payments to the consortium and maintain communication between our sponsors and our accounting groups. I serve as liaison between consortium sponsors and RCRL research staff, and I also serve as a point of contact to answer questions, help solve any problems, and assist with getting sponsors the information they need. I work with our web group to maintain the RCRL website and keep it updated with all RCRL activities and current research data.

At the end of the day, my goal is for my research staff to be able to stay focused on what is really important in our group: their research.

To Drill or Not to Drill— That is the Question

Dr. Svetlana Ikonnikova



“Game changer,” “hype,” “myth,” “revolution”—these words are used in discussions of something called *shale gas*. Shale gas has been in the Earth for millions of years, geoscientists have known about it for 100+ years, and yet most people, including leading economists, did not know about it until about a decade ago. And of those who knew about it, only a handful thought it could be produced economically and at the scale we see now. So when I first heard about shale gas, I wanted to know answers to the same questions people now ask me: (1) How much shale gas is there? (2) Will production last or stop abruptly in the near future? (3) Is it economical to produce? (4) How much shale gas could be produced, given the price and current technology? These are key questions because the world is changing and resource availability, environmental impact, and energy-source affordability all play crucial roles in both economic development and the geopolitics of countries.

What I like about my work, though, is that it satisfies my curiosity and helps to enlighten and educate others. I see the study of shale gas as a great way to serve the public and enjoy my research!

Working in a team of geoscientists, engineers, and economists, I dig deep, literally, to find answers to these questions, unraveling the shale-gas story. The study of shale gas starts underground, with a geological analysis, which allows creation of rock-quality maps and determination of resources underground. Next, technical analysis, physics, and engineering help us move upward—addressing above-ground questions such as the economics of drilling and production outlooks. We also use observed production to estimate and predict future recovery. Numbers can be fascinating, telling a story of the past *and* the future: how shale gas

flows, how drilling technology develops, how much we can expect from a well. Calculating and calibrating the drainage areas of existing wells,



Photo courtesy of Google Earth. Aerial imagery captured June, 12, 2011.

From geology to technology and the future of the field—drainage areas (in red) of existing wells, showing space left for future drilling.

creating maps of undrained and undrilled areas—these are steps in exploring the play that can answer the first question and approach answering the second, third, and fourth. When economics is well grounded in facts, it serves its purpose and can help predict the future. The production outlook that is underpinned by an understanding of underground issues and shale-gas production provides a clue about future shale-gas contribution to the U.S. energy balance and, hence, promotes a healthy economy.

Nevertheless, it began to look to me as if the fun would stop when we had finished the Barnett Shale study. A methodology had been developed, and lots had been learned about shales, but was that it? And then, turning to the Fayetteville Shale play, we discovered new surprises, and, after that, with the Haynesville study, new challenges cropped up again. No, my work never gets boring! No repetitions—just new discoveries and more excitement!



Shale-Gas Potential in the U.S.

John Browning

In 2011 the Bureau received a grant from the Alfred P. Sloan Foundation to study the four largest gas-shale plays in the U.S. The goal of the study is to determine the ultimate production potential from this vital resource and then to describe what development will require in terms of drilling rigs, wells, gas prices, etc. The team is trying to describe the geologic and operational drivers of well performance. My role on the team is to develop an analytical approach for determining the estimated ultimate recovery from individual wells, to determine the area drained by existing wells, and then to determine the potential for future wells.

I also help develop the economic and production models that describe the pace of development and resulting production forecast. Our analytical approach has been developed for Barnett field but will next be applied to Fayetteville, Haynesville, and Marcellus fields. Each of these fields exhibits its own geologic and producing characteristics that require modifications to the analytical approach. Once completed, we expect the study to be one of the most thorough and transparent assessments of U.S. shale-gas potential in existence.

We hope to develop insights that would be important to industry, policy makers, regulators, and consumers. Our initial work is introducing an innovative way of predicting well production through decline analysis. Our approach, although simple to apply, better reflects fluid-flow theory through nanodarcy rock and helps resolve several

difficulties encountered when using conventional decline analysis. Our analysis is indicating relatively high reserve recovery across relatively limited

drainage areas, implying greater opportunity for infill drilling. Our findings also imply greater technically recoverable resources than most assessments indicate. Estimated ultimate recoveries depend on prevailing natural gas prices, but, in any event, the study indicates that substantial reserves remain and many wells will be required over decades for full development. Our approach helps identify the most prospective areas for future development



and likely economics returns. And, finally, we are seeing how the potential in shale-gas plays can be expanded in higher price environments, and we can identify key technology limitations which, if overcome, would most impact potential resources. Many of these topics have been partly addressed in proprietary studies, but our study will be comprehensive, multidisciplinary, transparent, and widely available to industry and policy makers. In the process, we are building expertise and capability within the Bureau that can be a foundation for further research investigating shale plays around the world.

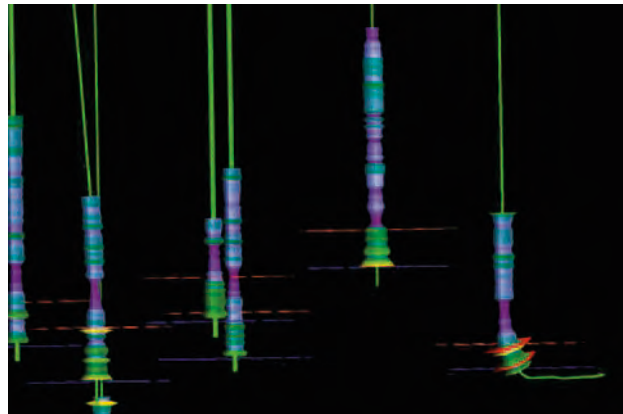
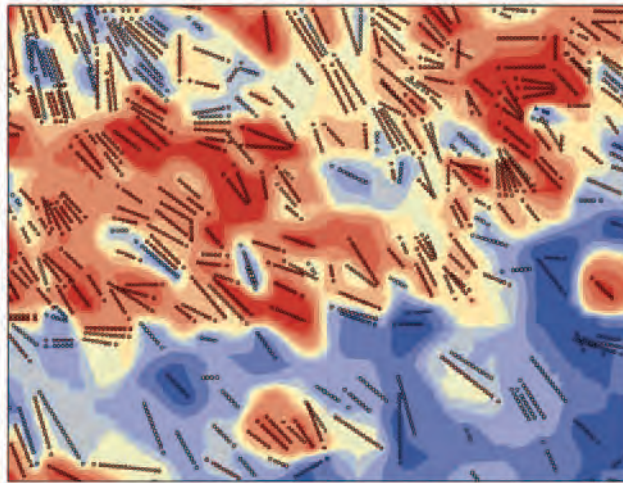
The image represents the drainage area of Barnett wells drilled in southeast Wise County. The Barnett study is attempting to determine the optimal number of wells needed to drain the available resource adequately.

Determining the Past, Visualizing the Future...

Susan Horvath



As a Research Scientist Associate and GIS Analyst at the Bureau, I am responsible for collecting and analyzing both surface and subsurface datasets related to energy production. My current involvement with the Sloan Foundation Grant—*The Role of Shale Gas in the U.S. Energy Transition: Recoverable Resources, Production Rates, and Implications*—focuses on unconventional gas production from five of the top shale-gas plays across the U.S. The goal of this study is to make publicly available a comprehensive perspective and comparison of these natural gas shale plays.



My role in this project allows me to draw on prior experience in both geology and GIS, constructing relational databases for complex queries and geostatistical modeling, as well as engaging in the aesthetic aspect of map presentation. Over the past several months, I've produced cross sections and well log correlations, log-porosity grids, geologic structure and production maps, Google Earth (KML) files, and time-interval animations. Many of these maps and grids are developed by working closely with other Sloan Foundation Grant members—economists, petroleum engineers, and geologists from the Bureau and other institutions. This unique aspect of the study ensures that this exciting,

comprehensive approach is balanced by interdisciplinary expertise.

When not working on the Sloan Foundation Grant, I'm often training or assisting other Bureau members and graduate students in using GIS software and metadata practices in the STARR (State of Texas Advanced Resources Recovery) group. I meet with other U.T. and Bureau GIS analysts to discuss future technology, data-storage needs, and best practices and methods. As in any technical field, continually preparing for new software developments and industry trends is crucial. I therefore maintain

active memberships and participate in both national and local GIS and geological organizations.

The types of data-analysis challenges found by different methods operating between multiple software suites can change daily. In particular, questions encountered through the Sloan Foundation Grant and other Bureau projects have been many and varied. For example, my images have the ability to illustrate the surface and subsurface datasets that I have regularly encountered. The creative freedom I've been given to address these challenges has been both educationally and personally gratifying.



Energy and Space Frontiers

William A. Ambrose

I am a Research Scientist at the Bureau—a sedimentologist specializing in energy research with an emphasis on oil, gas, and coal—vital commodities for America's energy future. I am currently the Principal Investigator for the STARR (State of Texas Advanced Resource Recovery) Program, which is dedicated to working with oil and gas operators to increase oil and gas production in Texas.

I have recently been involved in a quest to explain the three-dimensional anatomy of East Texas oil field, the largest oil field in the Lower 48 states in terms of original oil in place. East Texas oil field fueled America's war effort in World War II and continues to produce oil in thin (commonly < 20 ft) sandstone beds that were deposited in ancient deltas, even though it first started producing more than 80 years ago.

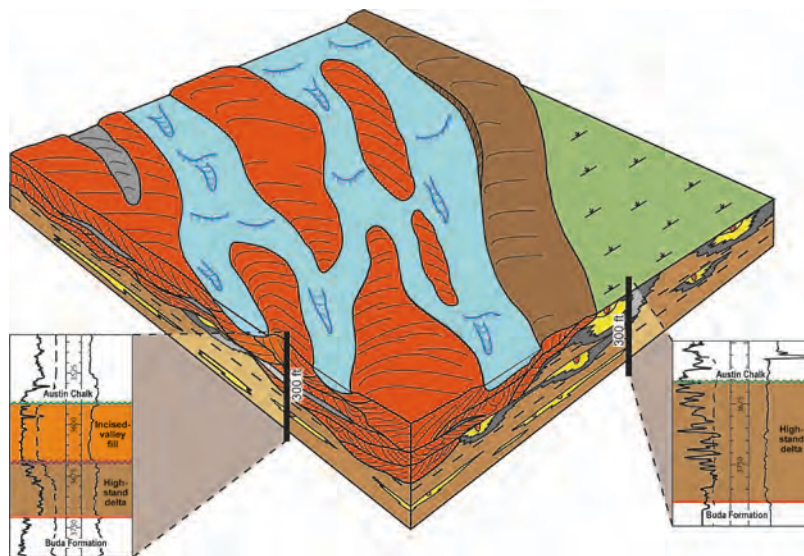
I also work with the EMD (Energy Minerals Division of the American Association of Petroleum Geologists) coal committee, serving as committee chair. I remain active in research on clean coal in Texas, where CO₂ that can be captured from coal- and lignite-fired power plants can be used for enhanced oil recovery (EOR) in mature oil fields, providing economic incentives for additional coal production in the state. Texas has a wide variety

of areas that can be targeted for new clean-coal facilities. These areas can be chosen by mapping the co-occurrence between coal- and lignite-

bearing formations, groundwater and surface-water resources, and CO₂ sinks in brine formations for long-term CO₂ storage or in mature oil fields with potential for EOR.

I also have an astrogeological side to my career and have published and presented research on the Moon, both at the Lunar

Planetary Science Conference and in a Special Volume by the Geological Society of America. I am currently Co-Chair of the AAPG Astrogeology Committee and Co-Editor of AAPG Memoir 101, *Energy Resources for Human Settlement in the Solar System and Earth's Future in Space*, released at the end of 2012. The U.S. Constellation project, although cancelled in 2010, was designed to return U.S. astronauts to the Moon by 2020 and support long-term human settlement, as well as in situ development of mineral and energy resources for infrastructure on the Moon—fuel and life support materials for humans while in space and energy and mineral resources for humans on Earth. However, we have not lost this dream, and the initiative has passed to a number of entrepreneurs and private entities working, sometimes with NASA and sometimes independently, to fully realize these goals.



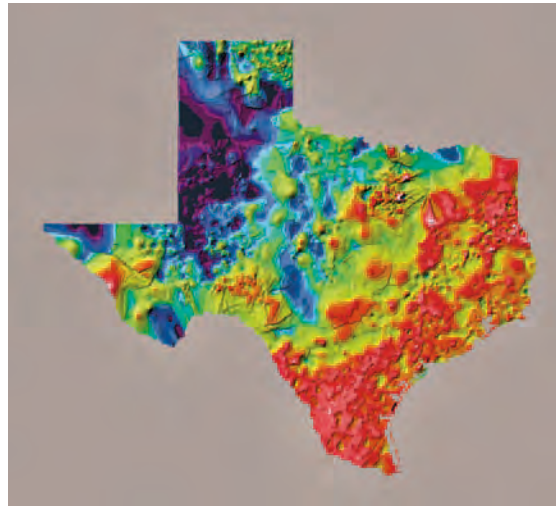
Three-dimensional anatomy of oil reservoirs in East Texas field.

The Heat beneath Our Feet

Bruce L. Cutright



Geothermal energy is heat derived from magmatic or volcanic areas where near-surface molten rock has heated circulating groundwater to temperatures near or above the boiling point. The thermal energy from these sources can then be extracted to drive electric generators. Yellowstone National Park is a classic example of this type of environment, although power generation from the park is prohibited. But



what if this geographically limited source of energy were available everywhere? What if the natural heat from the Earth's interior could be tapped from any geographic location and used to drive electrical generators with no fuel costs and no CO₂ emissions? And what if this source of energy were renewable, sustainable, available 24 hours a day, 365 days a year, and economically competitive with fossil fuels, nuclear power, and wind and solar sources of energy production?

Technological advances over the preceding 2 decades in drilling technology, formation stimulation, and thermal-energy conversion have widened the prospects of extracting heat from the subsurface as a viable energy technology. The massive investment that the petroleum industry has expended over 150 years in developing subsurface reservoirs is applicable to extracting heat from deep geologic formations, and, with technologies from the industry, the economics of geothermal-energy production continue to improve. The ultimate comparison of various power-producing methodologies is the "levelized cost of energy," and geothermal energy is now comparable to oil, advanced coal-fired generators, wind, concentrating solar, and photovoltaics and is only a few cents per kilowatt hour more expensive than advanced natural-gas turbine generators.

If this is such a great idea, with both economic and environmental arguments supporting development of geothermal energy production, then why have we not seen aggressive growth in this energy sector? The U.S. Department of Energy Geothermal Technologies Program concluded that developers would expand production of geothermal energy to include deep, hot sediments if information

on the nature of the resource were made more easily available. As a result, and funded by two significant grants from DOE, the Bureau Geothermal Research Group (of which I am a part) has been assembling data on promising geothermal zones in Texas over the last 2 years, building on earlier studies conducted by Bureau researchers in the 1970's and 1980's. We are now making this information available to the public to encourage private entities interested in developing geothermal resources.

We are not stopping at defining the resource, however. In cooperation with Lawrence Berkeley National Laboratories, we are also investigating how geothermal energy can be extracted from deep, low-permeability sediments or crystalline rock using supercritical CO₂. This pilot study may open up development of hot, dry rock formations or enable the transition of tight-shale-gas formations to geothermal energy production after they are depleted of natural gas. If proven successful and economically competitive with other sources of renewable energy, supercritical CO₂ heat extraction may solve the problem of CO₂ emissions from fossil-fuel plants and expand the extractable resource base of geothermal energy significantly. Stay tuned!



We Will, We Will Rock You

Beverley DeJarnett

I am lucky—I am really lucky. I'm a geologist, and like most geologists, I love to look at rocks. I am trained to try to understand the stories that rocks have to tell. And... at my job at the Houston Research Center (HRC), I get to look at different rocks every single day. How lucky is that? If any of you have ever lived in Houston, you probably know that no outcroppings of rocks are to be found anywhere near Houston. We Houstonians have to drive at least to Huntsville to see real rocks—in place—on the Earth's surface.

But what you may not know is that here in Houston, the Bureau holds a vast collection of rocks from beneath the Earth's surface. The Bureau's HRC, along with the Austin and Midland Core Research Centers, houses millions of boxes full of rocks collected from all over the United States, or, rather, all *under* the United States. When companies drill for petroleum or coal, they collect samples of the rocks as they drill through them. When a well is drilled through rocks with a standard drilling bit, the rocks are ground and crushed, and they come up to the surface as sand-grain-sized fragments called *cuttings*. Sometimes a special drilling bit is used, and a 30-ft or longer cylinder of rock is collected. These cylinders of rock are called *cores*, and they can range from 1 to 6 inches in diameter and up to hundreds of feet in length.

These rock samples offer us our only direct view of the Earth beneath our feet, and the rocks provide the "ground truth" for accurate interpretation



Presenting interpretation at a core workshop.

of well logs, seismic, and other tools used to interpret the Earth's subsurface. Sampling these cuttings and cores has allowed for an explosion of testing with the birth of new technologies. Geoscientists studying results of these analyses have been able to make great advances in our understanding of issues such as where petroleum can be found,

geohazards, and paleoclimate. Technology evolves so quickly—who knows what questions we'll be able to answer in the future? But to answer these questions, we must have the raw material available to be used as samples. Hence, an important Bureau mission is to preserve this invaluable rock material and make it easily accessible to the scientific community for future research.

My work includes the following: raising awareness of the Bureau's collection of cores and cuttings; helping patrons find rock material that will help them in their work; describing and integrating the rocks into industry projects; teaching core workshops; conducting outreach about the importance of rocks and geoscience to K-12 and university students, as well as to the public in general; and working with industry to secure donations of rock material and monetary contributions that will ultimately allow the HRC to become self-sustaining. And, of course, every day there are new boxes of rocks to open and new stories to learn from the rocks!

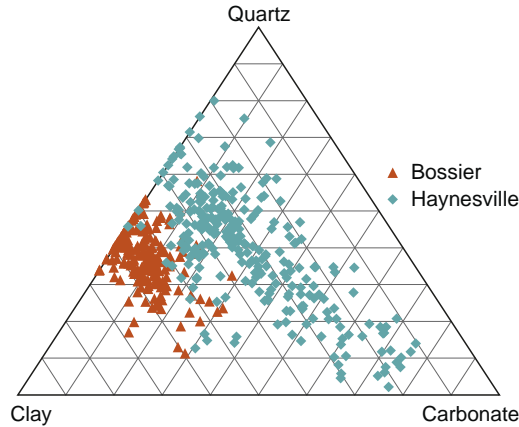
Petrophysical Analysis of Unconventional Reservoirs

Ray Eastwood



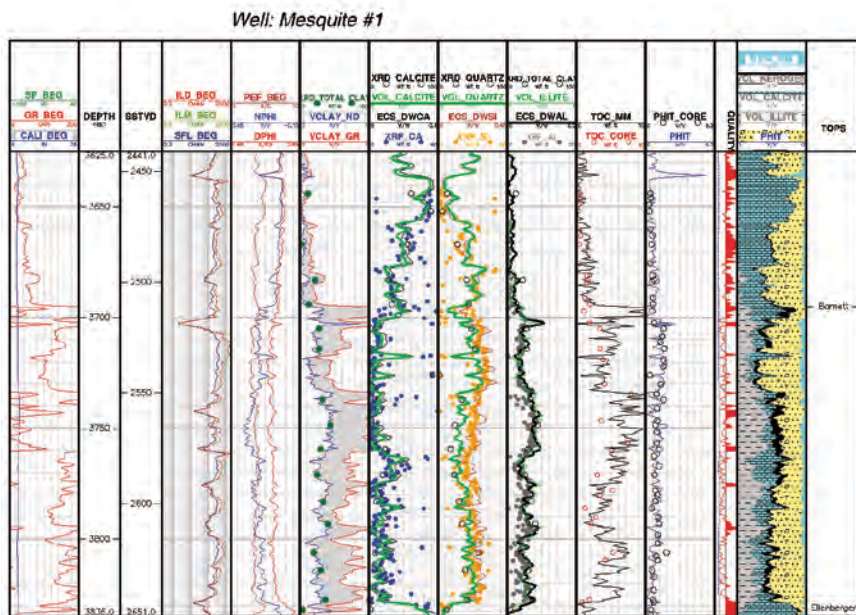
I do petrography from well logs, well, sort of—textural information is a challenge! Well log responses reflect the volumes of constituent minerals and fluids contained in a rock in the subsurface. Petrophysical evaluation of unconventional reservoirs requires a shift of paradigm from that used for conventional reservoirs and one that is based on carbonate

and shaly sandstone analysis. Petrophysical analysis can no longer simply target either carbonate or shaly sandstone analyses. In petrophysical terms, unconventional reservoirs are mineralogically complex, and they have submegascopic grain sizes that challenge conventional methods of examination/characterization and contain variable



amounts of kerogen. Use of optimized solvers for multiple log inputs enables improved log model results that are consistent with geologic observations of lithology and porosity and kerogen variation. Comparison with XRD, XRF, and conventional core data enables calibration of log model results. These results, in turn, enable characterization of reservoir properties

for uncored wells—given enough logs. Still, the main issues for characterization of unconventional reservoirs are the same as for characterization of conventional ones—porosity estimation, permeability estimation, how these properties are affected by lithology variation, and estimation of hydrocarbon volume.



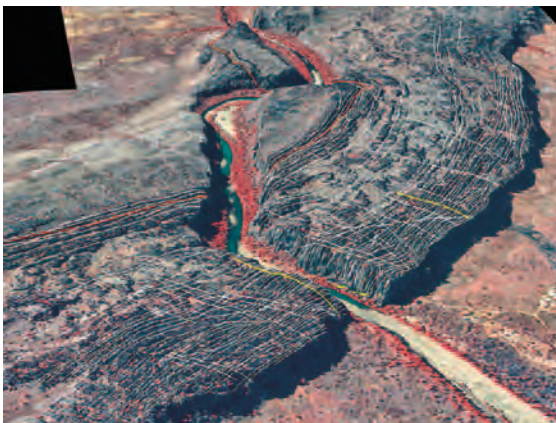


Fractured Carbonates: from Deposition to Reservoir

Dr. Ned Frost

I am a Research Associate at the Bureau working within the State of Texas Advanced Resource Recovery (STARR) group, which is dedicated to working with operators of all scales to increase hydrocarbon production within Texas. I joined the STARR group in 2011 as a carbonate stratigrapher. To date, I have worked on projects designed to find new opportunities for hydrocarbon production in Texas in the Austin Chalk, residual oil zones of the Permian Basin, and the Carboniferous of the Bend Arch and Fort Worth Basin. These research endeavors involve a mix of both outcrop and subsurface data. Prior to joining the Bureau, I worked for ConocoPhillips Subsurface Technology as a Senior Research Geologist on projects in Lisburne field (Alaska), the Permian Basin (west Texas and New Mexico), the Precaspian Basin (Kazakhstan), and the Browse Basin (northwest Australia).

My research interests, as well as my professional experience, are focused on the interaction of carbonate stratigraphy and structural geology. More specifically, I am interested in investigating



Syndepositional deformation features (white lines) flanking a carbonate platform margin in Devonian reef complexes, Canning Basin, Western Australia. Modern scarp at right side of range approximates the platform margin. Image includes infrared data and is rendered in false color, with vegetation showing up as red.

syndepositional deformation in carbonate platforms and the evolution of mechanical stratigraphy in carbonate strata. Syndepositional deformation (see figure) and related fluid flow are becoming increasingly recognized as key controls on reservoir quality and well performance in high-relief carbonate platforms. My recent research in the Canning Basin (Western Australia) and the Guadalupe Mountains (New Mexico) has focused on investigating how syndepositional deformation in carbonate strata influences stratal architecture, diagenetic fluid flow, and resultant rock properties (for example, dolomite; see figure), and pore-network development from the depositional into the burial realm.



Dolomite halo (light-gray and white rock) flanking syndepositional fracture in Dark Canyon, Guadalupe Mountains, New Mexico. Plug holes, approximately 2.5 cm wide, provide scale. Unaltered wall rock is darker gray and brown.

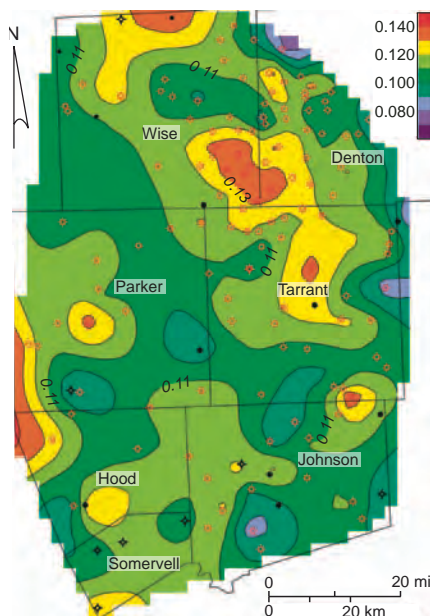
Sedimentary Rocks: Reservoir and Recorder

Dr. Qilong Fu



Oil and gas are trapped in sediments and sedimentary rocks, and ultimate recovery of these hydrocarbon reserves (conventional and unconventional) depends largely on our understanding of the reservoir, as well as innovative technology. About 60 percent of the world's oil and 40 percent of the world's gas reserves are contained in carbonate reservoirs, and depositional facies and stratigraphic architecture may be major factors controlling occurrence and quality of these hydrocarbon reservoirs. In addition, postdepositional processes (diagenesis) are critical to characterization of subsurface reservoirs because these processes largely determine the distribution of pore space governing the flow behavior of hydrocarbon reservoirs. Chemical reactions of limestone and dolomite that are caused by circulating fluids are of vital importance to an understanding of the spatial and temporal evolution of carbonate deposits. My research involves integration of sedimentological, stratigraphic, petrographic, and petrophysical approaches to better characterize facies pattern and geometry, dolomitization, diagenetic alteration of rock fabric, pore-size distribution, and flow properties in carbonate reservoirs.

Petroleum industries and governments across the globe have increasingly looked at unconventional resources as a viable source of oil and gas production owing to the increasing scarcity of conventional hydrocarbon reserves. Improved reservoir knowledge and increasing advances in technology make production of unconventional resources economically viable and more efficient. Two of the most important play types are shale



Density-log-porosity contour map of the Barnett Shale pay zone, based on 146 wells in the Fort Worth Basin.

gas and tight gas. Shale-gas and liquid reservoirs, once ignored by operators seeking easier plays and faster returns on investments, are boosting U.S. natural gas and oil reserves. My research interests in unconventional resources include facies description and mapping, stratigraphic correlation, pore modeling, petrophysical evaluation, resource assessment, and play analysis of gas shale and tight-gas sandstone.

Sedimentary rocks, which cover most of the Earth's surface, are truly the history book of Earth and its past life. Composition and fossil records of sedimentary rocks are a window to that past, allowing us to learn about the organisms, climate,

catastrophes, and geography of Earth in the past. I am interested in extracting paleogeographic, paleoenvironmental, paleoclimatic, paleo-oceanographic, and paleoecological information recorded in sedimentary rocks and exploring the scientific significance of the information, which is crucial to aiding our understanding of Earth, both now and in the future.

I joined the Bureau in 2008 and have been involved in several research projects, such as synthesis of Wolfcampian platform carbonates in the Permian Basin and the petrophysics and origin of microporosity in the Albian Macea Formation, offshore Brazil. Currently I am conducting two carbonate-reservoir characterization projects and a gas-shale-reservoir characterization project. The objective of the latter is to provide the geological underpinnings of the top five shale-gas plays and develop useful parameters for reserve and production estimation.

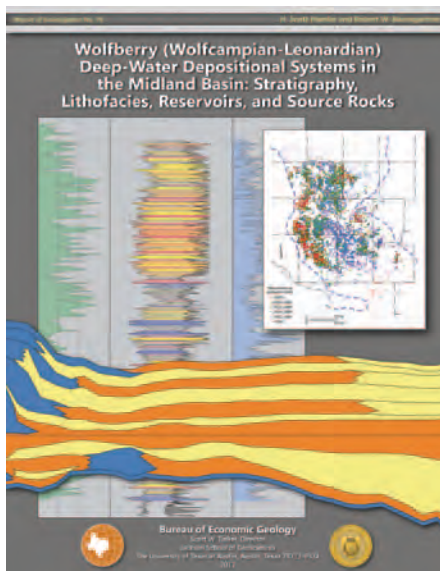


Stratigraphy is the Key

Dr. Scott Hamlin

Stratigraphy records Earth's history, and stratigraphic rocks contain natural resources. I study stratigraphy, mainly subsurface stratigraphy, to learn about Earth history and to assess resources. Resources of interest to me reside in the subsurface: petroleum and groundwater. Although my research alternates between hydrocarbon reservoirs and groundwater aquifers, the common theme is stratigraphy—the arrangement, dimensions, and compositions of sedimentary rock layers.

Sedimentary rocks—sandstones, limestones, and shales—and the fluids that fill and flow through their pores are the subjects of my research. Sediments are eroded, transported, and ultimately deposited in rivers and deltas and deep ocean basins, where they become buried and eventually transformed into rock. They retain, however, clues about their formation. I use these clues to reconstruct depositional environments and infer rock properties beyond the limits of data. Paleoenvironmental reconstruction is called depositional-system analysis, which is a powerful tool for resource assessment. Depositional systems, such as river deltas or submarine fans, have characteristic dimensions and properties, which can be modeled and have predictive power. Sandstones deposited in river channels are long and narrow, a simple but key bit of information when explorationists decide where to drill wells. In other words, depositional-system analysis reduces uncertainty in exploration for and development of fluids trapped in pores in sedimentary rocks. As an added bonus, I get a peek into the distant past—a



lush tropical river once flowed where barren desert now lies.

Stratigraphy provides a context for depositional-system analysis. Some stratigraphic layers are timelines subdividing the rocks that lie between them into time-stratigraphic intervals, and depositional-system analysis only makes sense within time-equivalent intervals. When did that tropical river flow, and what happened after it stopped flowing? Thickness changes in time-stratigraphic intervals can be related to rates of sediment accumulation, another key bit of information

when reconstructing past environments and inferring rock properties. Organic matter becomes sufficiently concentrated to form petroleum only if sedimentation rates are low.

I rely upon data collected in petroleum and water wells to study subsurface stratigraphy. Wireline logs are by far the most common form of subsurface data having widespread geographic distribution, and wireline-log data have been collected in hundreds of thousands of petroleum and water wells in Texas. Wireline-logging devices are lowered into wells where they record electrical, nuclear, and acoustic properties of rocks near the borehole. My job is to interpret rock and fluid compositions from these wireline-log properties. Actual rock samples (drill cores) are far fewer but are critical to the calibration of wireline logs. In 2012 I used these data and techniques to map stratigraphy and characterize resources in Permian unconventional oil reservoirs in west Texas and Cretaceous groundwater aquifers in north-central Texas.

Sandstones and Energy Sources

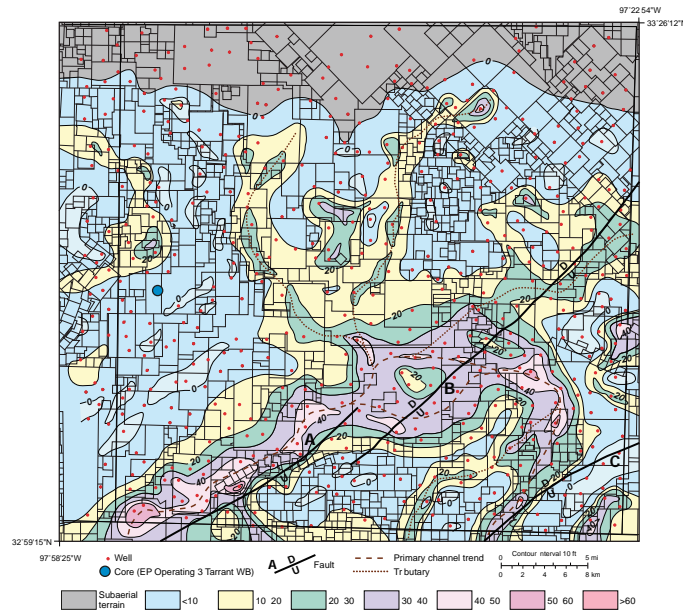
Tucker F. Hentz



For most of my career at the Bureau, I have been engaged primarily in the study of buried sandstone and shale deposits, the wide range of ancient environmental settings in which they were deposited, and their regional distribution in buried depositional basins. The ultimate goal of my investigations has been to gain a keener insight into the location

and distribution of commercial accumulations of oil and natural gas. Datasets that I have used in my studies include well logs (graphic records taken from petroleum wells that reveal a great variety of information about buried rocks at the well site), miles-long seismic profiles (synthetic representations of rock layering to many thousands of feet below the surface), rock cores (elongate, cylindrical columns of rock drilled out of oil wells), and thin sections (extremely thin, translucent slivers of rock viewed with a microscope that reveal details of burial history).

The data gathered for such investigations then help answer many questions. How do complexly stacked sandstone and shale layers correlate as time-equivalent layers across a basin, especially those strata that contain hydrocarbons? What are the primary trends of optimal-quality sandstones in a certain region? In what ways did faulting and folding of rocks during and after their deposition affect depositional pathways and sandstone-



reservoir distribution? A veteran Bureau research geologist for the past 30 years and counting, I have been asking these questions (among others) for quite a while and have investigated sedimentary deposits in many basins in Texas and nearby areas, such as the Anadarko Basin of the Texas Panhandle, the East Texas Basin, the Fort Worth Basin, offshore

Louisiana, and the Burgos Basin of offshore northeast Mexico.

In recent years, I have conducted much of my work in concert with colleagues of the Bureau's Project STARR (State of Texas Advanced Resource Recovery). This highly successful, multiyear project is funded by the State of Texas, and its goal is to assist oil and gas producers in their search for reservoirs within Texas. An elegant aspect of the project is that the industry partners need only provide their raw data to allow project members to, in turn, study their specified area of interest; no payment is required. Bureau geoscientists typically receive high-quality, cutting-edge data that can then be used in our publications, the lifeblood of our organization. Moreover, the State receives increased tax revenues from any new oil and gas production generated by the partner as a result of our assistance—a three-way, all-win situation that is the hallmark of STARR!

Extrapolating Rock Properties beyond Wells



Rodolfo C. Hernandez

One of the major milestones in the history of geosciences applied to the energy sector and particularly the oil industry has been the emergence of seismic data.

Seismic data have allowed the empty spaces between wells to be filled and have given us a better understanding of structures in the subsurface. Initially, seismic data were used to interpret the geometry of subsurface structures, and yet the progress that has been achieved in terms of seismic data acquisition and processing has enabled interpreters to characterize reservoirs in a quantitative way on the basis of the physical properties of rocks recognized using the seismic data. We can now determine what is beyond the wells on the basis of information provided by these seismic data. This breakthrough is one of the key reasons why I, as a geophysicist, decided to become a seismic interpreter because I can provide my colleagues not only an interpretation of the geometry of the subsurface, but also a quantitative interpretation of the rock's properties.

I am a geophysicist developing a seismic interpretation program for the State of Texas

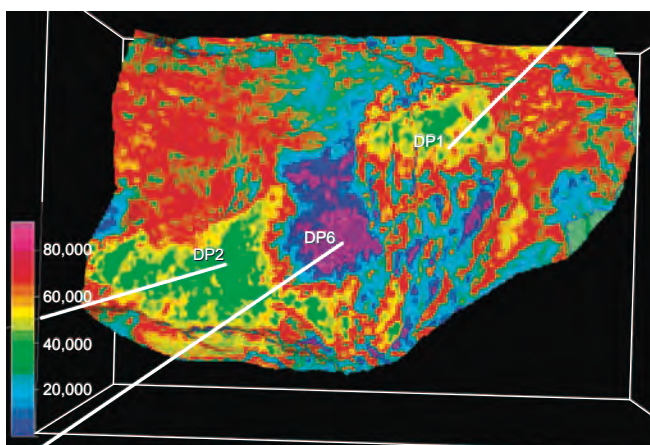
Advanced Resource Recovery (STARR) project. I am currently working on a structural interpretation of a 3D seismic dataset in the south Texas area. This

work is focused on definition of a framework for the area to allow identification of areas of interest to exploration and development operators.

During the execution of this project we have been defining structures associated with mobile shale and growth faults known as *minibasins*. Identification of such areas will

help these operating companies increase their production—a main objective of project STARR.

I have also worked on regional studies and basin modeling to identify new exploration plays in many basins in Venezuela (Maracaibo, Barinas-Apure, Eastern, and Columbus Offshore basin), as well as elsewhere in South and Latin America—Bolivia, Uruguay, Argentina, and Guatemala. I have broad experience in generating velocity and geological models for reservoir characterization, as well as studying AVO, seismic attributes, and seismic inversion.



Seismic reservoir characterization using gas-field acoustic impedance attributes.

Brittle-Zone and Hydrocarbon-Sweet-Spot Identification

Dr. Osareni Ogiesoba



With our country's recent new goal of near-term energy independence, exploration for conventional oil and gas plays within the Gulf Coast has moved from shallow targets to depths as great as 20,000 to 25,000 ft (6,096–7,620 m). Identification of hydrocarbon reservoirs at these depths, where sediments are overpressured, mostly shale dominated, and subdivided into subbasins by diapiric shales, is no trivial exercise. My research is directed toward answering questions such as where can hydrocarbon reservoirs be found? And is each shale diapir composed of a single shale column? Attempts to answer these questions have yielded some fascinating results—in particular, that most of the shale diapirs are composed of ejected materials from interbedded shales.

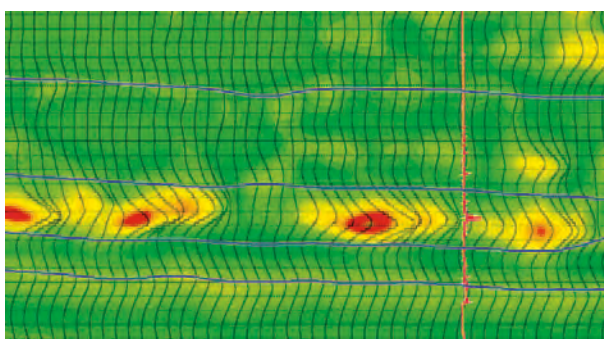
I also work on unconventional-resource plays. A challenge with unconventional resources is in the identification of locations of hydrocarbon sweet spots and brittle zones. Brittle zones are rock intervals that are more susceptible to fracturing and may contain abundant fractures and faults. Because fractures provide flow paths for hydrocarbons into production wells, significant work is being done locating and hydraulically inducing them. Fracture identification is therefore a major challenge confronting geoscientists and petroleum engineers. In formations such as the Austin Chalk and Eagle Ford Shale—a dual (conventional and unconventional) resource play—thousands of failed wells have been drilled because

of failure not only to identify the sweet spots and brittle zones, but also to establish the link between the two. Although fractures and hydrocarbon-

rich zones can be identified from core data, core information is limited to well location. For study of lateral variations in brittleness and sweet spots, 3D seismic data need to be used, even though the procedure is daunting. I have been investigating this problem for the past 3 years, and attempts to solve the riddle have led to inroads in isolating certain seismic attributes that can be used to

“X-ray” shale-gas/oil formations so as to identify brittle and high-resistivity zones. Computation of these attributes is cheap and fast and would offer the exploration community a way of quickly investigating shale-gas/oil formations to predict hydrocarbon-rich, water-saturated, and brittle zones.

As a Research Associate at the Bureau of Economic Geology, I am part of a multidisciplinary team integrating seismic and well log data to “X-ray” rock formations. My research encompasses conventional and unconventional resource plays in Texas, interacting with researchers and students in this exciting quest. I also co-supervise graduate student theses in seismic interpretation and anisotropy for fracture detection and noise attenuation. My work is funded by the STARR program, and results from my research help to guide the exploration programs of our corporate partners.



Transect through seismic attribute volume. Hot colors (yellow and red) correspond to high-resistivity and brittle zones within the Eagle Ford Shale and Austin Chalk Formations. Inserted log (red curve) is resistivity.



Siliciclastic Shelf Margins

Dr. Iulia Olariu

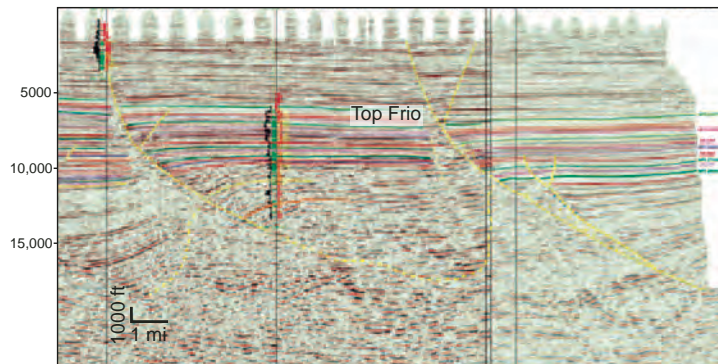
Continental-shelf successions are generally built from repeated cross-shelf transits of shorelines (mainly regressive-transgressive transits of deltas and estuaries),

a process controlled mainly by relative sea-level change and sediment flux. The shoreline separates nonmarine delta-plain and coastal-plain from marine-delta-front/shoreface and shelf reaches of the system.

Repeated transgressions and regressions of the shoreline, commonly on a timescale of less than 100,000 years, produce lateral and vertical migration of these facies belts, causing an overall aggrading and basinward-directed sedimentary succession—the shelf-margin prism. Basinal processes, such as tides and waves, additionally significantly influence the river output and along-shelf sediment dispersal. Shelf width and gradient, delta-front and coastal-plain gradients, and sea-level behavior and sediment flux all affect the way the shoreline moves. Geologists coming to an understanding of sediment dispersion at the basin scale using subsurface (wells, seismic, and core) and outcrop data is therefore crucial. The outcrop data provide information complementary to the subsurface data and help improve the correlation. Detailed outcrop models can also be used as reservoir analogs.

My area of expertise is clastic sedimentology and sequence stratigraphy, with a special focus on quantitative depositional architecture of both

shallow- and deep-water sedimentary systems. My research focuses mainly on the use of outcrops as analogs to hydrocarbon reservoirs, paying attention to architectural elements and depositional environments. I am also interested in linking and



Depth-converted regional dip-seismic line through the Oligocene Frio Formation.

extending outcrop studies using subsurface datasets (wireline logs, seismic, and core data) for subregional and regional studies. I have been using laser scanning technology (lidar) and 3D imaging systems (Sirovision) to investigate architectural elements in outcrops. At the Bureau, as a member of the STARR team, I have been involved in stratigraphic studies of the Wilcox and Frio Formations along the Texas Gulf Coast. The goal of the project is to subdivide the stratigraphy at a higher frequency (fourth order) time scale using well logs, cores, and seismic data. The main objective of this detailed subsurface mapping is to identify high-frequency regressive/transgressive cycles of sedimentation and to explain how the shelf-margin prism has been built. A more specific objective is to identify and link the depositional systems from shelf through slope to basin floor and to identify sediment fairways.

Black Gold

David Smith



I work as a database analyst for the State of Texas Advanced Resource Recovery Program, Project STARR, at the Bureau. The STARR Project receives its funds from the State of Texas to analyze Texas geology and then advise and assist operators on how to increase current production or discover new production. The State requires Project STARR to be revenue neutral—the project has to generate new revenue for the state that is greater

or equal to the amount that is appropriated to the project by the Legislature. Researchers generate field studies using advanced technology and application of sequence stratigraphic principles. This information and insight are then provided to STARR-partner energy companies, which often lack advanced research capabilities. Their successful drilling and production both power the STARR credit model, which verifies the revenue neutrality of the program. The additional oil and gas production caused by STARR's collaboration with company partners is subject to the standard State extraction tax known as the severance tax. STARR receives credit for a percentage of the new severance tax generated by the incremental production. Over the 17-year life of STARR, \$200 million in incremental severance tax credits has been generated by the program's results. This incremental value is approximately 10 times the State's investment in STARR over the same period.

After field research is released to the partner companies, I am tasked with following and tracking

their drilling progress in the field study area. After completion of the drilling well, I monitor and track well production.

I then compile both oil and gas production in a database that computes the income of the well. Once the income has been determined, the severance tax is estimated, and the percentage for the STARR project is calculated.

This process is repeated for every well throughout Texas that STARR researchers have

worked on. After a total is calculated, a progress report is created biennially. This process documents STARR's revenue neutrality.

I also play a secondary role within Project STARR, which is assistant to research scientists during their research analysis. Field research includes traveling to outcrops, collecting samples, measuring sections, conducting gamma-ray-spectrometer analysis, and describing fault trends and orientations. I assist researchers on industry-guided field trips in important geologic settings relating to oil and gas drilling. I also describe rock core in the core warehouse. Then, in the office, I work in a variety of software suites, using the software to track new permits for drilling. In addition, I retrieve production data for reservoir analysis; design and build a variety of maps, including production maps, well-location plots, and trend maps; correlate subsurface units across trends using well logs; and assist fellow STARR research scientists in locating any maps, production info, or well logs that they may need.



Photo courtesy of Greg Hebbourg.



Fluid Flow through Porous Media

Dr. Fred Wang

As a reservoir engineer at the Bureau, my job is to figure out how oil, gas, and water flow through porous media and how fast and how much oil and gas can be produced. I work with other Bureau geologists to study critical geological factors affecting fluid flow in reservoirs, with engineers to study new technologies to enhance oil and gas production, and with operators to develop economically viable technologies to maximize their field production.

In the last several years, I have extended my interest from conventional to unconventional resources, such as shale gas and oil. My biggest challenges have been to gain a better understanding of petrophysical and mechanical properties of organic-rich shales and their influences on fluid flow and production.

Shales, traditionally considered nonreservoir rocks and flow barriers, have been ignored by reservoir engineers for decades. The exceedingly successful

production performances from U.S. and Canadian shale resources, however have surprised the world and made organic-rich shales the most exciting reservoirs today. Nevertheless, properties of and fluid flow through these shale reservoirs are not well understood, and many theories about conventional reservoirs have failed when they have been applied. For instance, porosity, connate water saturation, and capillary properties of deep-burial

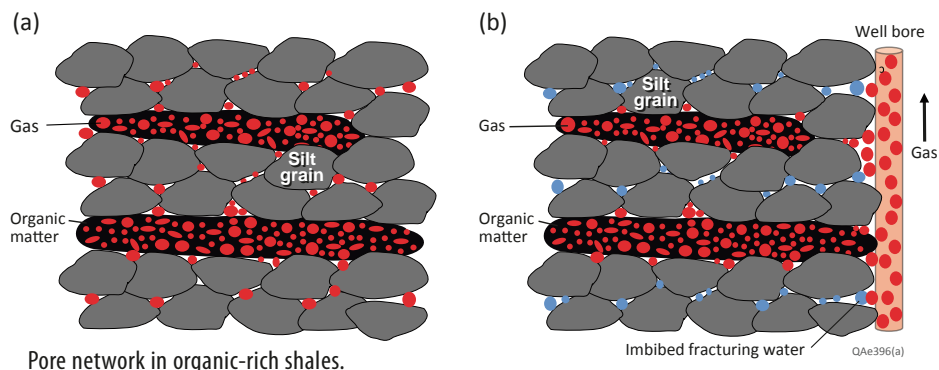
organic-rich shales are independent of their present-day depths. What is intriguing is that organic matter can be porous media, gas and water do not flow through the same pore network, and properties of organic-rich shales are strongly associated with their burial histories and maximum burial conditions.

The evolution of shale resources is currently revolutionizing geologic thinking and production technology. The joy of studying shale resources to me is that they are full of surprises and they force me to think differently.



Taken during a trip to Yangshuo, China.

Photo courtesy of Yvonne Chang



Seismic Data Patterns

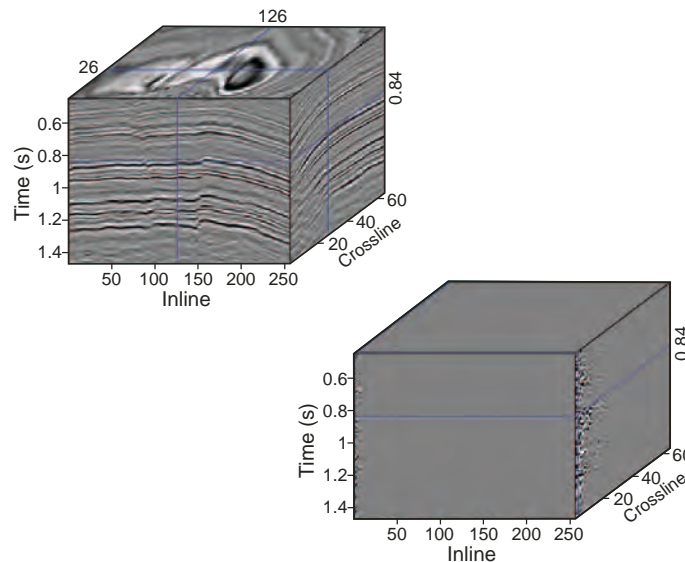
Dr. Sergey Fomel



Seismic waves occur in nature in relation to disastrous events (earthquakes and tsunamis). They can also be generated artificially, at a smaller energy, so that information might be gleaned from the subsurface. Since its invention during the oil boom of the 1920's, seismic reflection imaging has become an indispensable tool for looking inside Earth by converting reflection echoes of sound waves into images of the subsurface. The 3D seismic images that can extend to depths of thousands of feet are often the only information we have about Earth's structure between exploration wells.

One may think that seismic imaging is just an engineering tool, not a subject for scientific research. However, these images are so rich in complex patterns that they require the full power of scientific investigation to be understood and analyzed. Seismic data patterns come from two major sources: the physics of seismic wave propagation and the physics of deposition in sedimentary rocks. Discovering and coming to an understanding of these patterns and their relationship to the Earth's structure are a difficult but rewarding task.

A geophysics discipline, such as reflection seismology, is a mixture of several other disciplines: geology, physics, mathematics, and, increasingly with the development of computers, computational science. U.T. Austin is the home of some of the top computational scientists in the world and some of the world's most powerful



high-performance computing facilities. To foster collaboration between disciplines and to make full use of the local computational expertise, we have established the Texas Consortium for Computational Seismology (TCCS) as a joint venture between the Bureau and ICES (Institute for Computational Engineering and Science). The mission of TCCS is

to address the most important and challenging research problems in computational geophysics as experienced by the energy industry, while educating the next generation of research geophysicists and computational scientists.

The educational mission is especially important to me, and it is why I accepted a joint appointment as Professor in the Department of Geological Sciences, where I teach two graduate courses, Seismic Imaging and Multidimensional Data Analysis, and an undergraduate course, Mathematical Methods in Geophysics. The energy industry of the 21st century needs students familiar with state-of-the-art computational geophysics and ones capable of developing it further. The Madagascar open-source software package, which has been developed by my group in collaboration with many other groups around the world (more than 50 people have participated in its development!), provides a platform on which different computational algorithms can be implemented and compared with one another. Madagascar has proven to be an indispensable tool for both teaching and research.



Diffraction Imaging— a Way of Seeing the Invisible

Dr. Alexander Klokov

Hydrocarbons are the main source of energy nowadays, and to keep oil and gas production at the current level, finding and developing new deposits are crucial. Oil and gas accumulate in the subsurface according to certain laws, and some kinds of geological structures happen to be favorable to hydrocarbon accumulation. These structures are detected by a process called *seismic prospecting*. In this process, artificially generated waves penetrate the subsurface, interact with structures, and return to the surface. Returned waves are then registered in different places at different times, analysis of their arrival allowing for subsurface imaging.

A seismic wavefield contains two different types of energy—reflected and diffracted. Reflections are really extensive surfaces, such as bed boundaries. Diffractions originate from small but important geological objects—faults, fractures, and karsts. These objects define paths for hydrocarbon migration, and their correct mapping is critical to oil and gas prospecting and production. In spite of the importance of diffractions, however, conventional seismic has focused on reflected energy. In conventional seismic, the diffraction component is actually ignored and, in fact, is considered noise probably because of the weakness of diffracted energy—reflections are simply much stronger. Moreover, seismic records can become contaminated by large amounts of noise, and the noise can be as powerful as the diffractions themselves. These factors make diffraction analysis not trivial.

I have developed a method of diffraction extraction. In other words, we can now separate diffrac-

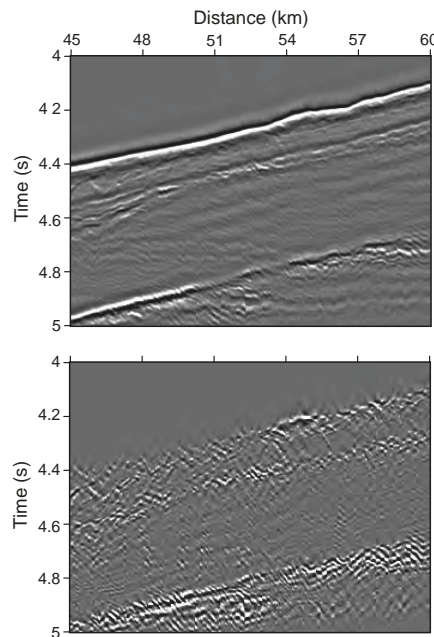
tions from reflections and noise. First, after the domain in which reflections, diffractions, and noise having different arrival-time signatures had been found, I derived equations to define the signatures. Using these equations we can now detect diffractions and extract them from the wavefield. This separate diffraction analysis allows us to construct maps of faults and fractures so as to retrieve information that is usually lost by conventional processing.

I have tested the method on several seismic datasets involved in different projects, and we see that diffractions allow for detection of a number of geological objects that are invisible after conventional processing—faults, fractures, salt-body edges, and gas-de-

posit boundaries. In a cavernous fractured reservoir, diffraction imaging has revealed cavern/fracture locations—areas that are well fractured and those that are not. This information can now be used in decision-making about well drilling.

A conventional image (top) shows the inclined layer at times of between 4.4 and 5 s. The diffraction image (bottom) reveals that the layer is well faulted and therefore of interest for oil and gas prospecting. In conventional processing, such faulting is not clearly visible, perhaps causing the loss of a promising prospect.

In the near future I intend to find a way of analyzing additional information carried by extracted diffractions—velocity of wave propagation and anisotropy features. Diffraction potentially provides the detailed information that is needed for finding hydrocarbons. For example, a low-velocity area may actually contain a hydrocarbon deposit!



Open Data Library for Computational Seismology

Karl Schleicher



As a Senior Research Fellow at the Bureau since 2011, I am interested in technology transfer, especially the practical development, implementation, and commercialization of new seismic processing technology. These things are what other members of the Texas Consortium for Computational Seismology (TCCS) group and I do.

Before joining the Bureau, I had worked for over 30 years for geophysical contractors, including GSI, Western Geophysical, GDC, PGS, and AGS, mostly in technology transfer. I have attended industry-sponsored research consortia meetings at Stanford, Colorado School of Mines, University of Houston, Delft University, and University of California at Santa Cruz. I have also implemented migration and velocity-estimation techniques and helped processing groups use the new programs. Many promising new technologies are slow to see broad commercial use because of problems in technology transfer.

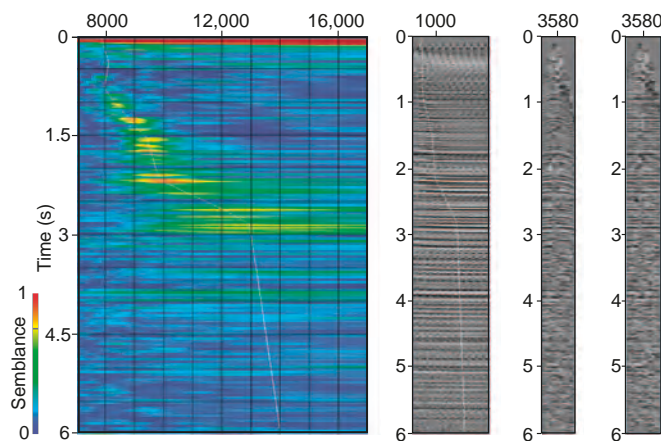
One of these problems we face is finding datasets for research, software testing,

demonstrations, and user training. In industry, processing groups help research and development groups. They provide data

expertise, including selection of a suitable dataset, previous results, detailed parameters, partly processed data for input, and an eye to evaluation of new results.

My project at the Bureau is an open data library that can be used to accelerate testing and validation of new seismic research,

especially at universities and small companies that do not have large data archives and processing groups. The library datasets support a variety of research, such as 2D, 3D, land, marine, random noise, multiples, and sampling. The datasets are supplemented with scripts that provide detailed processing sequences and parameters that can be used with or without modification. A general overview of the data, including images, suggested use, geographic location, and links for downloading seismic data and scripts is on the web at the Society of Exploration Geophysicists (SEG) wiki.



Velocity analysis of data from the open data library. Interactive display used to estimate subsurface velocity, a critical seismic processing parameter. Data, software, and scripts can be freely downloaded from the internet.

- 83** Gulf Coast Carbon Center
- 96** Water Resources
- 102** Coastal and Landscape
- 106** Water–Energy Nexus
- 107** Risk Assessment
- 111** Geologic Mapping

Environment

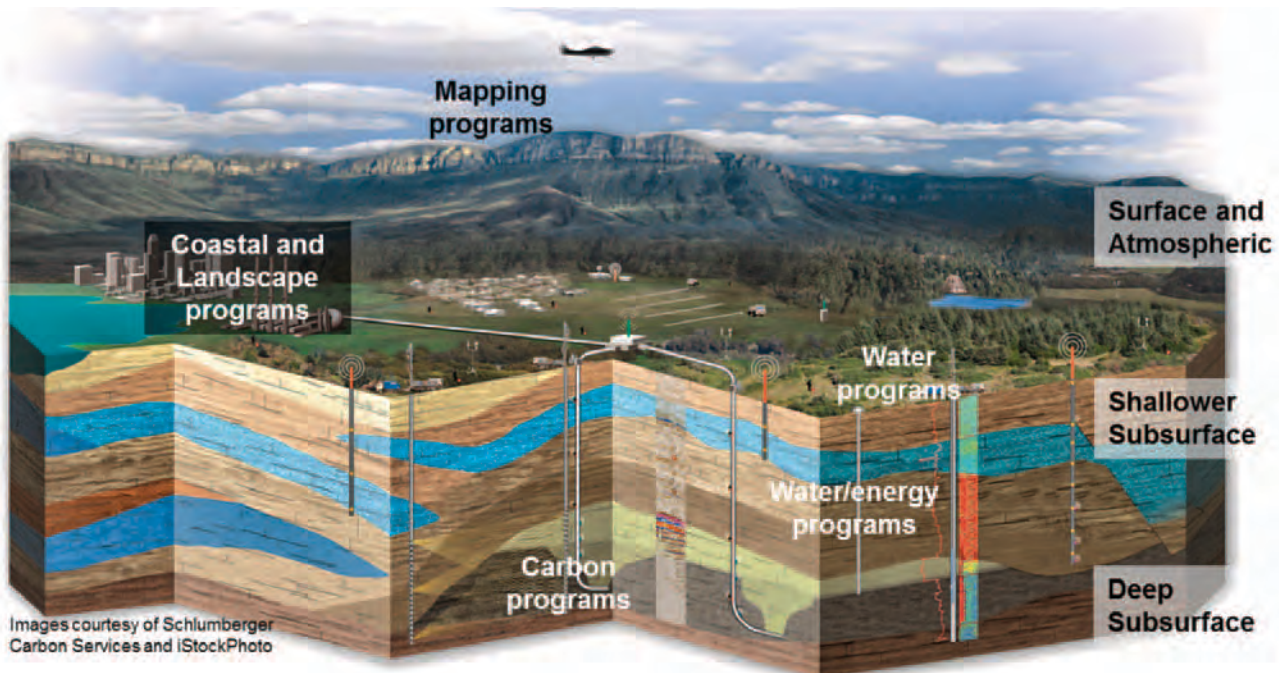
The Environmental Division at the Bureau comprises an incredibly diverse and talented pool of geoscientists and engineers. All told, we have close to 50 people, including permanent scientists, postdocs, and students. The diversity of our research is sometimes difficult to corral, but the graphic below schematically shows how we are roughly organized, from deep subsurface to surface geological and atmospheric environments.

Deep-subsurface geology is investigated mainly by scientists in the Gulf Coast Carbon Center, who study carbon sequestration and enhanced oil recovery. The water-energy programs look at issues of water use for hydraulic fracturing and risks associated with fluid movement from either carbon storage or fracturing. Closer to ground surface, our researchers focus on how land-use decisions affect groundwater and surface-water resources and quality and how water is used for municipal, agricultural,

and electricity-generating sectors. At ground surface, scientists assess coastal erosion, geological hazards, and landscape evolution, as well as geological mapping for statewide planning and economic geology.

Within these environmental groupings, our scientists approach environmental-geology questions from different angles within their individual disciplines. Together they try to explain the connections between water availability, land-use decisions, and energy systems and how these connections will evolve as Texas grows in population and natural resources grow in importance. Environment and energy are equally important to Texas, and treating them as connected systems allows us to find broader solutions to specific problems. Today our research results are of crucial interest to the public and decision-makers alike, not only in Texas but throughout the U.S.

—Dr. Michael Young





Wearing Different Hats at the Bureau

Dr. Michael Young

The Associate Director, Environmental Division, position varies by the week, by the day, and by the hour. My role at the Bureau is to help coordinate environmental programs in hydrology, carbon sequestration, water-energy and water-economics, coastal and landscape processes, and lidar and geological mapping. This coordination involves helping to unstick administrative processes, from proposals to purchasing, and to identify opportunities for research and collaboration between groups at the Bureau and within and outside the U.T. community. I help researchers at senior and junior levels with what they need to more effectively carry out their research programs, and I help develop larger program strategies that might yield cutting-edge research projects in 5 years' time. I remain involved in many aspects of hiring new staff, including both research and administrative personnel, and I help promote researchers through the ranks of University positions. I meet with numerous sponsors representing industry, State government, Federal government, and foundations to discuss our research and its value. The environmental programs at the Bureau span a huge range. And the challenge for me is understanding the technical goals, approaches, and results of each program enough to advocate to stakeholders and sponsors, but without becoming overly involved in the research or getting in anybody's way.

Along with these administrative duties, I also hold the title of Senior Research Scientist in the Jackson School, where I am involved in a variety



of studies related to water and energy resources and landscape characterization. I am a member of the Graduate Studies Committee in the Jackson School, where I teach and advise graduate students and serve on graduate student committees to examine and assess student progress as they

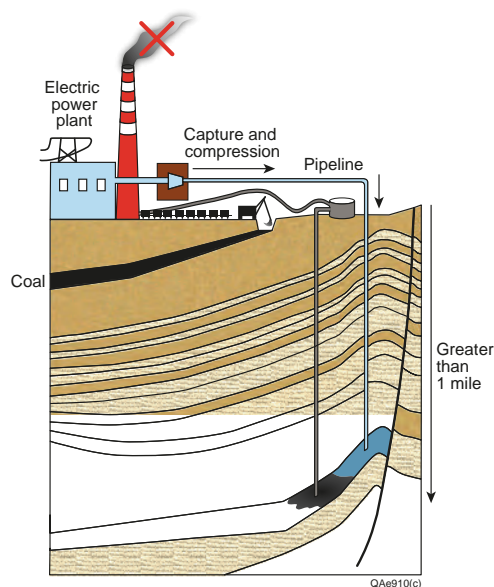
search for ways to graduate with their degrees. Outside of UT, I sit on committees of several scholarly organizations. Finally, at the beginning of 2013, I became Editor-in-Chief of the *Vadose Zone Journal*, one of the top peer-reviewed scientific journals dealing with processes in, and properties of, unsaturated soil and rock material. To briefly describe some recently completed research, I was co-PI on a project to examine the fate and transport of selected prescription medicines that might be applied to golf courses and parks in irrigation water. These compounds can be found in low concentrations (parts per trillion) in recycled water. In this 2-year study conducted at 4 golf courses in California and Nevada, we examined the transport of 14 target compounds through the grass and shallow soil. The compounds included anti-inflammatories, antibiotics, and antidepressants. We found that migration through only 75 cm of soil reduced concentrations by nearly a hundredfold in most cases. We found that the total mass of compounds that migrated deeper than 75 cm varied across golf courses, but that values were all less than 100 mg per hectare (equal to 2.2 acres). For perspective, one baby aspirin is 81 mg. The findings are being written into journal articles for future publication.

Field Tests to Monitor CO₂ in the Subsurface



Dr. Susan D. Hovorka

I have been conducting research as part of a global effort to demonstrate geological storage of CO₂. CO₂ is captured from large, stationary sources, such as electric-power-generation plants, compressed to dense fluid, and shipped by pipeline to a selected, permitted injection site. CO₂ is injected using many wells to place the fluid into a porous, permeable sandstone or carbonate unit that can be shown to sequester it in reservoir-pore systems for time periods relevant to atmospheric concentrations.



accepting and retaining oil and gas are valid to support models for injection of CO₂ for long-term storage. Measurements of two-phase plume evolution were more successful than anticipated in the CO₂-brine system. Project collaborators brought numerous tools, including pulsed-neutron well logs, downhole gravity, repeat crosswell acoustic, electrical resistance tomography, and natural and introduced tracers, into this environment, creating unique datasets that are used to match observed to modeled reservoir responses.

Our group at the Bureau, the Gulf Coast Carbon Center (GCCC) (www.gulfcoastcarbon.org), is one of the largest teams in the world working on geologic-storage research. The GCCC has leadership roles in monitoring significant field tests. Two U.S. DOE-funded storage tests closely monitoring CO₂ injected into brine-bearing sandstones of the Frio Formation (2004–2006) near Houston were the first of their kind. Two tests at Cranfield, Mississippi, oil field starting in 2008 have extensively monitored large-volume CO₂ injection to demonstrate and compare the well-known mechanisms for CO₂ EOR with large-volume storage in adjacent brine-bearing formations. Monitoring injection into brine allows measurement of two-phase fluid flow obscured in oil-field settings to be measured in interwell settings, leading to inputs that can be used to constrain conceptual and numerical models. The GCCC is providing monitoring expertise to two large-volume commercial projects sourced by captured CO₂.

Key results of field tests confirm that analogs showing performance of the subsurface in

In experiments, adequate characterization to predict reservoir response to two-phase flow was found to be the weakest link in making predictive measurements, with faster-than-expected migration of CO₂ occurring in three cases and slower than expected in one case. This finding suggests that pore-volume occupancy is lower than modeled, perhaps by a factor of two. Extrapolating this result suggests that ultimate plume size might be larger than modeled. However, as the plume evolves, saturation matches the model more closely, moderating the mismatch between modeled and observed size.

Another body of work has considered detection of situations where CO₂ was not retained. The GCCC team borrowed technologies from gas storage, contaminated-site assessment, and wetlands evaluation to create innovative approaches to detection of leakage. I list the broad spectrum of results from the GCCC team because of my emphasis on mentoring both professionals and the public on robust information about this currently relevant technology.



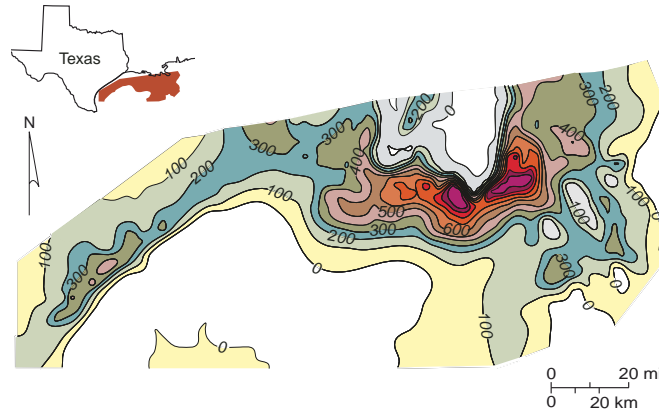
What Lies Beneath?

David L. Carr

How much space occupies the rocks beneath our feet? Where is it? Under your house or in another state? And how deeply is it buried? What's in the space? Is it water, brine, oil, natural gas, or something else? Can we extract and use it, or can we use the space for storage? These are questions I spend most of my working life trying to answer.

Answering these questions requires detective work, which is, incidentally, fun! First, I gather any information that might be pertinent to the problem. Scientists refer to this information as data. Because I work mostly on sedimentary rocks—rocks composed of small bits of older rocks, like sand grains—that lie thousands of feet or miles below the surface, most data I gather come from oil wells. These data include core samples that are actual pieces of deeply buried rocks and well logs—long graphs of physical properties such as density, electrical resistance, and sound velocity versus depth. Sometimes, when a well has produced oil, gas, or water, information is also available on volume, pressure, temperature, and fluid type(s).

If we're lucky, we might also have seismic reflection data, which we collect by making sounds on the surface and then 'listening' to the sounds bounce off underlying rock layers. Seismic data have lower



Total amount of pore space within middle and upper Miocene sandstones of northwestern Gulf of Mexico. Areas with brightest colors indicate highest pore space, running approximately parallel to present-day shoreline—greatest Miocene sandstone porosities occur in fossil shoreline deposits that were once deltas, barrier islands, and beaches. Map used to estimate volume of CO₂ possibly sequestered in these reservoirs.

vertical resolution than that of a well log, but they can 'see' nicely along the layers in between widely spaced wells. If we combine strong vertical resolution from well data and strong horizontal resolution from seismic data, we can get a pretty good idea of layer depths, thicknesses, internal characteristics, and rock types, and sometimes even detailed measurements of pore space and

the presence of natural gas. It's really cool when it all comes together in what's commonly called a *geologic model*. Then we can use the model to answer a variety of questions—where's the best place to drill for oil? Where can we dispose of greenhouse gases like CO₂? Funny how activities that seem to be polar opposites use the same data and methodologies to get answers, eh?!

We gather the data, combine them, and analyze them using computers. These require that the data be digitized, which can be a large and tedious task. We're lucky to have a number of talented undergraduate and graduate students, many of who gain entry to our programs 'in the trenches' digitizing data. A humble start, but most of these young geologists and engineers go on to acquire subsurface skills that they take to industry upon graduation. Contrary to the Rolling Stones song, I CAN get satisfaction from that!

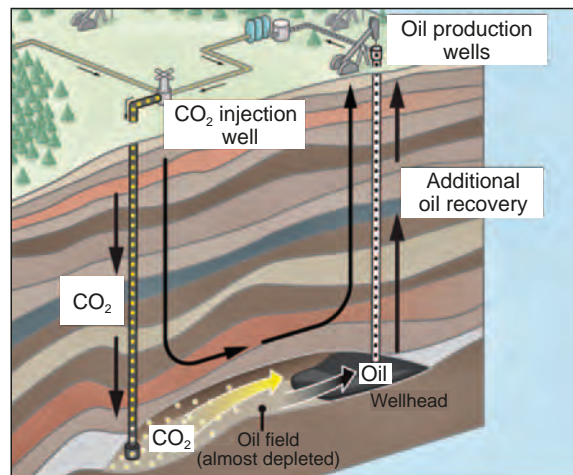
Fluid Flow in the Subsurface— Why We Should Know about It

Dr. Seyyed Abolfazl Hosseini



Down through geological time, fluid (brine, oil, and gas) has been very slowly moving around in the subsurface to finally settle down in a pressurized environment under an impermeable caprock to create our current oil and gas reservoirs. Production from these reservoirs currently provides a large part of the energy that humans use in their daily lives. To produce these resources at the rates that can address world energy demand, we need to have a grasp of the physics and processes that control the movement of oil and gas in porous rocks in the subsurface. Drilling of a well in these pressurized reservoirs provides a conduit for fluid to flow upward into storage facilities and pipelines and finally to refineries and related industrial plants. Sooner or later (depending on the regional energy of the reservoir), however, pressure in these reservoirs falls, and eventually oil and gas may no longer flow naturally to the surface, causing a huge part of these valuable fluids to remain in the subsurface. One obvious solution that industry can use is to repressurize the reservoirs by injecting a less-valuable fluid (like brine) and/or undesirable gases (like CO₂) into the reservoirs. This injection in turn creates a complex subsurface system in which

multiple fluids (brine, natural gas, CO₂, oil) come in contact with reservoir rocks, which then need to be modeled and optimized. These interactions are



Injection of CO₂ from injection well pushes oil to producers to increase recovery of oil from subsurface. In the end, undesirable CO₂ will be trapped in the subsurface and not valuable oil.

important to ensuring that we produce these resources at a maximum efficiency by finding the best locations for drilling the wells, maximizing spacing between the wells, and establishing efficient injection and production rates, etc. All these parameters should be designed in such a way as to ensure that injected fluids have maximum contact with oil to push it to the producing wells.

As a Research Associate at the Bureau with a Ph.D. in Petroleum Engineering and a

specialty in modeling fluid flow in the subsurface, I work in a multidisciplinary community of researchers (especially geologists), graduate students, and postdocs to model fluid flow in the subsurface using cutting-edge numerical simulators. For example, in CO₂ enhanced oil recovery projects on the Gulf Coast we are interested in finding out whether injected CO₂ remains completely in the reservoir (sequestered) and efficiently sweeps the trapped oil. Much of our research is supported by the Department of Energy, and we work in close collaboration with operating oil companies as well.



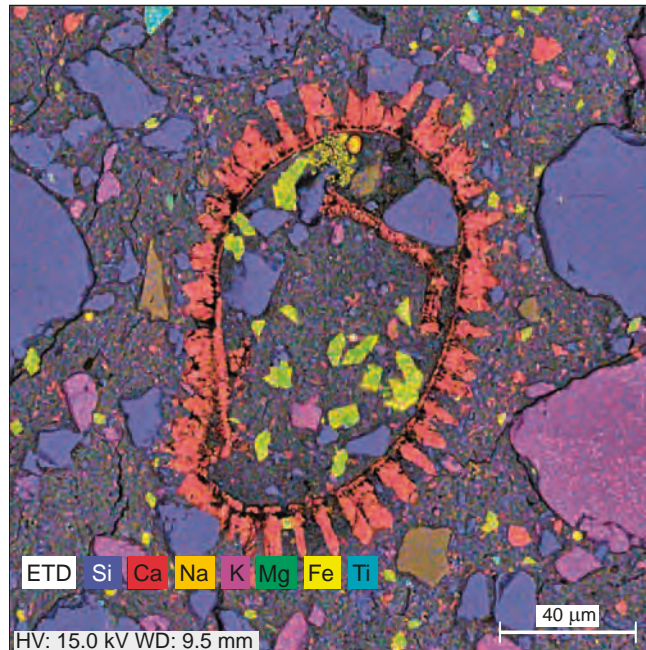
Science between Rocks and Fluids

Dr. Jiemin Lu

Many geoscientists are fascinated by the interactions between rocks and the fluid within them. Earth's crust, on which we live, is composed mostly of rock and fluid. The process of sediments turning into rock includes numerous chemical reactions between certain minerals and fluids such as water, oil, and gas. From the very beginning, when sands and muds are deposited on riverbed or seafloor, they are undergoing certain chemical and physical changes by interacting with the fluids in the pore spaces

between sediment grains. Rock properties after lithification depend largely on the types of pore fluids and mineral reactions that occurred during burial (diagenesis). Rocks must have porosity and permeability for fluids to move through them and be stored in them. Almost all pore space of the upper crust is filled with water and small pockets of oil and gas. On the other hand, some rocks that are tight and impermeable provide the seals for hydrocarbons and waste gas (such as carbon dioxide) to be trapped underneath. Chemical reactions between rock-forming minerals and fluid can be critical factors for certain rocks becoming good reservoirs and others becoming cap rocks.

Understanding physics and chemistry associated with fluid flow and rock-water interactions in reservoir rocks and cap rocks is important for successful hydrocarbon exploration and carbon



Scanning-electron image showing fossil chamber (maybe an ostracod—red) filled with clay, quartz (blue), feldspar (pink and brown), and diagenetic minerals such as ankerite (yellow-green) and pyrite (yellow).

sequestration. By studying the history of rock-fluid systems, we can improve our understanding of the present (for hydrocarbon exploration) and our ability to predict the future (for carbon sequestration). For such an understanding, however, many critical questions need first to be answered. For example, how do minerals react with different pore waters/gases, and how do the reactions affect porosity and permeability? Why are some rocks able to trap gas

for millions of years while others are leaky? How do fluids move in various rocks? Each of these questions requires life-long investigations by many scientists. At the Bureau, I work with researchers of various academic backgrounds to close these knowledge gaps. My daily activity is to interrogate the rocks, water, and gases that we obtained from the deep subsurface. I employ various techniques to observe the texture and pores in rocks, to learn about their chemical compositions, to determine their isotopic signatures, and to test chemical reactions under pressure and temperature. Collaborating with a number of academic and industrial partners, my group and I carry out large-scale field experiments by pumping fluids into rocks over 3 km deep and studying their chemical and physical behaviors using numerous state-of-the-art technologies.

Being Fluid

Dr. Tip Meckel



Society's need to utilize the subsurface is evolving. Traditional extractive practices continue (hydrocarbon and groundwater production) as the need to reintroduce fluids grows in importance (industrial water and CO₂ disposal). The volume, movement, and accumulation of fluids in the subsurface therefore remain important aspects of geoscience investigation. I pursue research across a range of spatial scales relevant to advancing understanding of these important topics, focusing on buoyant-fluid behavior.

At small scales, I have been investigating the impact that depositional heterogeneity has on the migration of fluids under capillary flow (oil, gas, and CO₂ migration). I have developed a technique that combines traditional 2D sedimentary-relief peels of unconsolidated clastic deposits with modern digital-laser scanning and 3D microscopy techniques to represent spatially varying rock properties (for example, permeability, threshold pressure) related to sedimentary fabrics at native resolution (millimeter to meter scale). Simulation of buoyant-fluid migration using these high-resolution models contributes to our understanding of hydrocarbon losses during migration and residual trapping of CO₂.

At the field scale, I have participated in two of the most highly monitored industrial-scale demonstration projects on CO₂ sequestration to date in the country. The research I lead as part of the ongoing SECARB Partnership project focuses on monitoring and predicting pressure response to large-scale injections and interaction of pressure with structural discontinuities. A novel aspect of SECARB monitoring is the transfer of data from



Deployment of high-resolution marine 3D seismic equipment in the Gulf of Mexico, July 2012.

the subsurface (>10,000-ft depth) to a web-based server for real-time analysis. These data represent the longest continuous measurement of pressure and temperature related to CO₂ injection to date. Another novel aspect of current research is use of "above-zone monitoring" to verify well integrity for several wells that

penetrate the injection horizon. The goals of this monitoring are to demonstrate CO₂ containment and to explain subsurface pathways of CO₂ migration, both within the injection zone and in relation to discontinuities, such as existing wells and faults.

At the basin scale, I currently lead the Texas research initiative to identify CO₂ storage potential in State offshore lands. I have started the first marine high-resolution 3D seismic-acquisition research program at the Bureau, having successfully collected an initial 50-km² survey this past summer off the south end of Galveston Island. These data reveal unprecedented imagery of moderate-depth stratigraphy, providing a tool that spans shallow- to deep-imaging technologies. Integrated with deeper seismic-reflection data, studies have focused on imaging faults and analyzing vertical fluid migration potential in a hydrocarbon-prone basin being considered for CO₂ storage.

As a researcher with the Gulf Coast Carbon Center for the past 6 years, I co-teach a course in Carbon Sequestration. I also supervise graduate-student research and am involved in teaching the undergraduate field-geology summer program in the northern Rocky Mountains.

Carbon Cycling: from Tropical Caves to Carbon Capture and Sequestration



Dr. Patrick Mickler

Aside from trips to tourist caves as a kid, my first experience with a wild, undeveloped cave came soon after I left high school. I was fortunate to have had no experience in modern mountaineering or caving techniques, so the 50- to 60-ft free-hanging drop, and later climb, into and out of a pitch-black vertical pit using a knotted hemp rope did not strike me as the wrong way to do things. Regardless, the several hours exploring the cave had me hooked, and they came to an end only when, with my back and chest wedged against the sides of the vertical fracture, I could go no farther. I was sure the crack opened up again in the next 10 to 20 ft and continued, unexplored into the hillside. Since then I have explored caves in the U.S. and Barbados, West Indies. Highlights include examining a saltpeter mining operation from the early 1800's in Kentucky, which was left intact when abandoned; hauling scientific equipment through flooded passages 2 ft in height; and visiting a one-eyed pack rat, deep in a cave, whose prized possession was the head of a child's doll.

These early experiences in caving got me interested in how caves can be used as archives of past surface conditions. Caves hold records of the Earth's past in layers of sediment deposited on cave floors, which contain remains that range from extinct Pleistocene animals and archeological artifacts to seeds and pollen from plants that once lived above the cave. Caves also contain speleothems such as stalagmites, which can form



Photo courtesy of Staci Loewy

over tens of thousands of years and contain records of changing water chemistry, some of which is driven by climate change in the changing composition of the speleothems' calcite. Of particular interest to me have been changes in the carbon-isotopic composition of CaCO_3 speleothems and how these

changes are being controlled by current climatic conditions. Our speleothem group at U.T. has found seasonal changes in cave-air CO_2 concentrations dramatically affected by the carbon isotopic composition of speleothem calcite. Our observations on the cycling of carbon from atmosphere to soil organics to cave atmosphere have allowed us to make important conclusions regarding the use of speleothem-based carbon-isotope records on paleoclimate reconstructions.

New work at the Bureau has focused on the potential impacts of CO_2 in carbon capture and storage (CCS) and enhanced oil recovery (EOR) projects. Specifically, how does injected supercritical CO_2 affect brine-rock interaction, chemistry, and reservoir mineralogy? Also of interest is how high CO_2 levels will affect near-surface potable-water supplies if CO_2 were to leak from the target reservoir into near-surface environments. Although CCS projects and cave research seem very different topics, they both rely heavily on an understanding of carbon cycling through water-rock-soil-atmosphere systems and the effects of CO_2 on aqueous geochemistry.

On Carbon Capture, Utilization, and Storage

Vanessa Nuñez-Lopez



Did you know that only about one-third of the U.S.-established oil resource base has been produced or placed into proven reserves? It's true. A massive volume of about 400 billion barrels (Bbbl) of oil, out of about 600 Bbbl of original oil in place, is still technically stranded and impatiently waiting for new technologies to come help produce some of it! The latest release from the U.S. Energy Information Administration puts the 2010 crude oil proved reserves at 25.2 Bbbl. These are barrels that are—with at least 90 percent confidence—recoverable with existing technology and under existing economic and political conditions. Existing technology, you say? Yes! So if new technology is developed, can we increase our domestic-oil proved reserves just by being able to produce more oil out of our existing fields and not simply by adding new discoveries? Yes! And this fascinating, unfolding story is the focus of my research.

Carbon dioxide (CO₂) enhanced oil recovery (EOR) is a technology that targets the residual oil in depleted oil reservoirs by injection of CO₂. The CO₂, which acts like a solvent, helps produce this residual oil by *cleaning* the rock like kerosene would clean a grease stain out of a shirt you wore when you fixed your car. CO₂ is a solvent when introduced into an oil reservoir, which is great, but a greenhouse gas when introduced into the atmosphere, which, in substantial amounts is... not so great. So, what if we captured the substantial amounts of CO₂ that are emitted every day by



fossil-fuel-burning facilities, like power plants, and use that CO₂ for EOR? Well, that is a technology called *carbon capture, utilization, and storage* (CCUS). In this technology, the CO₂ is not only utilized to increase the final recovery of depleted oil reservoirs, but it is also ultimately stored in the deep geologic formation that constitutes the oil reservoir. Not all the injected CO₂ stays in the reservoir, though. In fact, it cycles. Some of it is produced with the oil, separated from the oil, injected back into the reservoir, and produced again. However, we know

that ultimately a significant volume of CO₂ will stay in the reservoir, and we also know that the reservoir will take care of that CO₂ just like it did during the millions of years it stored the oil and gas it still contains today.

So that the volume of CO₂ that can be stored in an oil reservoir after an EOR process is documented, the CO₂ needs to be monitored and accounted for during the operation. We at the Bureau's Gulf Coast Carbon Center (GCCC) are designing two monitoring, verification, and accounting (MVA) programs that will be implemented in two commercial EOR operations, both of which will utilize CO₂ from industrial facilities. The U.S. Department of Energy is funding these two projects through the American Recovery and Reinvestment act of 2009. I am currently managing one of these projects, as well as providing petroleum engineering support to several GCCC projects.

Will the Real Molecule of Stored CO₂ Please Stand Up?

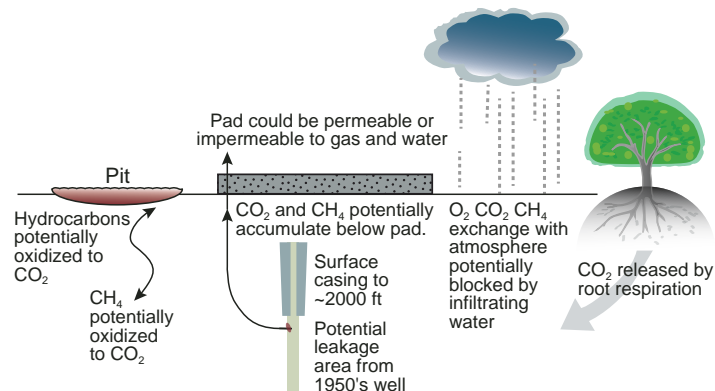


Dr. Katherine Romanak

At the Bureau's Gulf Coast Carbon Center (Principal Investigator, Susan Hovorka), my colleagues and I study the many aspects of carbon capture, utilization, and storage (CCUS). CCUS is one option for lowering greenhouse-

gas emissions by capturing CO₂ produced from industrial processes (that is, power generation and cement and iron production) and injecting it into deep, stable, geological formations for long-term storage. In CCUS, CO₂ can be utilized to enhance hydrocarbon recovery in depleted oil and gas fields. During this process, some CO₂ is dissolved, mineralized, or otherwise trapped in pore spaces, thereby ensuring that the CO₂ is stored away from the atmosphere, where it cannot contribute to global climate change.

CO₂ storage sites have required monitoring to ensure that CO₂ remains underground and to demonstrate that near-surface resources such as potable groundwater and the biosphere are protected from potential adverse effects of leakage. The challenge of near-surface monitoring is that CO₂ exists normally in aquifers and sediments and its concentrations are always changing as a result of natural processes. So how can we tell whether the CO₂ we see is natural or the result of a storage-formation leak? A big part of my work is devising new ways of separating a leakage signal from ambient CO₂ in the near-surface. The ability to distinguish stored from natural CO₂ is important for many reasons—one of which is to allay concerns of



those who live above carbon storage sites. For example, if a farmer living above a CCUS site sees changes in his land, he might wonder whether those changes are due to CO₂ rising from a storage formation. With the methods

we have devised to detect a CO₂ leakage signal, this question can be answered quickly and easily. Using our methods at a farm above a CCUS site in Saskatchewan, Canada, we were able to assure the farmer that no leakage was occurring on his property.

What are potential environmental outcomes if CO₂ were to leak into the near-surface? How could we know or predict the effects? We approach these problems from many different angles using laboratory experiments, modeling, and industrial and natural analogs. For example, in using natural systems to predict the outcomes of leakage, we can observe the near-surface in areas that are naturally CO₂ rich; however, we must be careful when drawing comparisons between natural systems and engineered injections. CO₂ flux, temperatures, time scales, and subsurface geologic structures can differ greatly between these two environments. For best results, we combine what we learn from all of these approaches to ensure that an accurate picture of potential outcomes is constructed. Once we understand these issues, we can ensure that CCUS is a safe and effective method of mitigating global climate change.

Travels with the Bureau: in Search of Solutions



Rebecca C. Smyth

My Bureau travels have taken me to Texas oil fields; the Orinoco Delta of Venezuela; every major municipality in Honduras following Hurricane Mitch; Texas Gulf Coast and southern California shorelines; ancient cities of Rumkale and Zeugma in the Euphrates River valley, Turkey, and Butrint, Albania; and the Powder River Basin of Wyoming. Since 2007, I have been back in Texas oil fields. The obvious solutions (in the title) are crude oil, hydrocarbon gases, brine, seawater, fresh water, and, more recently, carbon dioxide (CO₂); less-obvious solutions are the sometimes elusive causes of environmental impacts, both human made and natural.



I have found forensic solutions to geological puzzles such as (1) why crude oil started flowing in the sink of a house in Jones County, (2) how a leak in a natural-gas pipeline caused a house in Brazoria County to explode, (3) why crude oil began seeping from the bottom of the Colorado River in Wharton County, and (4) why fresh water from wells in an oil field in Scurry County became too salty to drink. Everyone knows that we benefit from oil and gas exploration and production. What everyone may not know is how much work goes into finding solutions to environmental impacts arising from our thirst for energy. In the past, science and industry could not fully explain deep-underground movement of oil, gas, and water or how activities at the surface affect underground natural resources. Things we learn partly through discovery of environmental damages show how to improve oil-field practices so that future impacts can be reduced or avoided.

I have been part of a Bureau team that makes digital topographic maps of the Earth's surface using airborne topographic lidar. It's been a blast flying in small aircraft firing a laser through a hole in the plane's underside or helping the pilot navigate using gps, and then helping combine the many different data-sets to calculate distance and gps solutions, on which lidar-map accuracy depends. Uses of Bureau lidar maps have included (1) studies of shoreline

change and identification of sensitive biological habitats along U.S. coasts, (2) community planning to rebuild areas destroyed by natural disaster, (3) preservation of archaeological sites, and (4) pipeline design and water-retention ponds in areas with rugged terrain.

I have recently focused on carbon sequestration—technology for capturing CO₂ from industrial sources, transporting it to a suitable location, and injecting it deep underground. We have a great team of geologists, engineers, managers, and students who collaborate on solutions to how CO₂ moves in the subsurface. My work includes (1) identifying U.S. locations having geologic layers with the right properties for long-term CO₂ storage, (2) designing and managing investigations of water quality over oil fields where naturally occurring CO₂ has been injected for enhanced oil recovery (EOR) since the 1970's, and (3) managing a Bureau team characterizing the subsurface of an oil field where CO₂ captured from the largest U.S. coal-fired power plant will be injected for EOR. We're also designing a monitoring program showing that CO₂ is not leaking back into the atmosphere.

And Now for Something Completely (?) Different ...ok, How about *Somewhat* Different?



Ramón Treviño

Energy powering our civilization comes mostly from fossil fuels (oil, natural gas, coal), and I've spent most of my professional career helping to discover or increase production of the former two by improving understanding of the geologic framework of oil and gas fields. Because these fields are generally many thousands of feet below Earth's surface, no one has ever seen a petroleum field. So a petroleum geologist must develop a picture of the subsurface that is based on scant and varied data. Sometimes outcrops of the same or similar rock strata are available. Alternatively, data may include small pieces (for example, cores) of actual rocks or samples of fluids contained in the rocks, although cores are generally expensive and rarely available. Luckily other data are available to explain rocks' (and their fluids') properties, such as the rocks' ability to transmit or resist electrical charges or sound (seismic) energy. Similarly, most rocks emit minute radioactive particles, some emitting more than others, which provide clues about which rock type occurs at which particular location and depth level. Other data supply information about tiny holes (pores) in subsurface rocks. Almost all rocks have pores, but some are smaller than others, and some are more interconnected than others. Knowing the amount, nature, and interconnectedness of pores is critical to understanding the subsurface-rock system in question and how to most efficiently extract the petroleum that we need for our modern lifestyles.

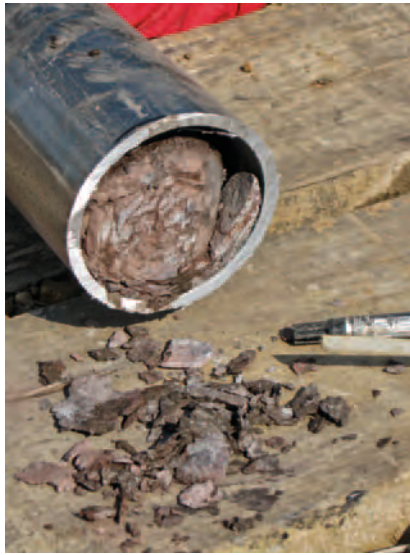
Recently many older oil fields have been rejuvenated owing to better scientific

understanding of their framework and new engineering techniques for extracting their oil and gas. In some cases, carbon dioxide (CO₂) has

been injected into fields whose oil production was declining or had ceased altogether—a technique called *enhanced oil recovery* (EOR).

Whereas improved understanding of Earth's subsurface has allowed geoscientists to provide us with the fossil fuels needed to power our society, improved understanding of Earth's atmosphere has led to a growing realization that the main byproduct of burning fossil fuels, CO₂, is probably significantly warming the planet. Some think the science is not "definitive," but mounting

evidence strongly suggests as much. Therefore, for the last 5 years, I have been using my knowledge, experience, and training in both subsurface geology and business administration to work as a project manager with my colleagues (in the Bureau's Gulf Coast Carbon Center), who conduct research to essentially reverse the extraction process that was the focus of the earlier part of my career and, instead, inject and sequester the CO₂ (a.k.a. *geo-sequestration*). We use the same principles and many of the same tools used in petroleum geoscience to explain how injected CO₂ moves and resides in rocks and fluids of the deep subsurface. Commercial EOR provides many data and even opportunities for experiments to test our hypotheses. So now our improving understanding of subsurface rocks may allow us to someday safely *reinject* into the subsurface the CO₂ (originally extracted as petroleum and coal) instead of *storing* the CO₂ in Earth's atmosphere as we currently do.



Assessing Potential Impacts of Geological CO₂ Sequestration on Groundwater Resources

Dr. Changbing Yang



Carbon capture and storage, in which CO₂ is captured and injected into deep saline formations, holds great promise as a way of mitigating the effects of greenhouse gases on global climate. However, concerns exist about the possibility of CO₂ leakage into overlying aquifers through preferential pathways, such as faults and active and abandoned wells, potentially impacting groundwater. My research focuses on potential impacts of CO₂ leakage from storage formations on groundwater resources. In addition, I am attempting to determine how groundwater-chemistry monitoring can be used to detect CO₂ leakage signals. Thanks to funding from the SECARB Phase III project, in collaboration with researchers from the University of Mississippi, Mississippi State University, and the Bureau, I was able to conduct a 3-year groundwater chemistry survey. Groundwater samples collected from a shallow aquifer at the Cranfield site were analyzed for baseline characterization of groundwater chemistry, including current groundwater quality, and discovering which geochemical processes dominate groundwater quality in this aquifer. Results of the study were presented in a paper that has been accepted for publication in the *SPE Journal*. However, the groundwater survey did not address potential impacts of CO₂ leakage on shallow-groundwater quality. Waiting for CO₂ leakage at the Cranfield site is impractical because



Push-pull test conducted at Cranfield site for assessing potential impacts of CO₂ leakage from geological CO₂ sequestration on groundwater drinking resources.

injection of CO₂ into the 10,000-ft formation started just 3 years ago. Instead, we conducted a set of batch experiments in which we took aquifer sediment back to the lab, placed it in flasks filled with groundwater, and bubbled CO₂ through the flasks. Water-chemistry change in the flasks provided a means of evaluating potential impacts of CO₂ leakage into an aquifer. Accuracy of

such laboratory experiments is limited because of the small amounts of aquifer sediments tested. We have also used numerical modeling to evaluate potential impacts of CO₂ leakage on groundwater quality, although modeling will be accurate only if model parameters are used correctly. We then proceeded to conduct push-pull tests, which were funded jointly by the SECARB Phase III project and the Water Research Foundation. In a push-pull test, groundwater recharged with CO₂ is injected into the target aquifer, given time to react with aquifer sediments, and then pumped out for analysis. This year we conducted two push-pull tests in different types of aquifers—the carbonate-rich aquifer at the Brackenridge Field Lab and the carbonate-poor aquifer at the Cranfield site. Results have proved exciting and have been summarized in a manuscript submitted to a peer-reviewed journal. The push-pull test appears to be valuable in assessing potential impacts of CO₂ leakage in groundwater at geological CO₂ sequestration sites.

What Goes in the Subsurface Stays in the Subsurface



Dr. Khandaker Zahid

Since the beginning of the Industrial Revolution, significant amounts of greenhouse gas have been threatening our atmosphere by raising our global temperature.

Carbon dioxide (CO₂) is one such gas that, in addition to various other sources, comes from fossil fuels being burned to produce energy and electricity. In a measure to reduce the rate of CO₂ emissions to the atmosphere, scientists and engineers have been working tirelessly to find ways of turning CO₂ into a commodity and sequester it underground. One way to utilize CO₂ is by enhancing

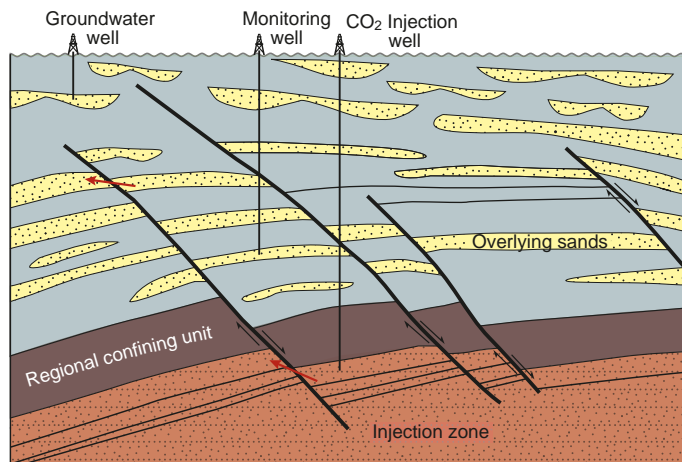
production of declining oil fields—a process called *EOR* (enhanced oil recovery). However, if CO₂ is to be injected in the oil reservoir to recover more oil, it needs to be monitored to ensure that the injected CO₂ stays in the reservoir and does not return to the surface.

At the Gulf Coast Carbon Center at the Bureau, my colleagues and I work on monitoring the CO₂ in the shallow subsurface by using different tools after it has been injected into both saline formations

and oil-containing reservoirs for EOR. To be able to track the pathway of this CO₂, however, we need to have a grasp of not only the subsurface geology

of the injection zone, but also the regional confining unit and the overburden. This is where my work comes into play, which is to map different structural and stratigraphic aspects of the subsurface geology and build models that resemble these elements. I am involved in subsurface mapping of EOR sites for detecting the heterogeneity and discontinuity of Oligocene and Miocene sands, modeling faults

for highly compartmentalized injection zones, and mapping the upper extent of the faults for their possible reach into the shallow groundwater. The reservoir models that I make are used by engineers to run simulated scenarios so as to speculate on the plume sizes of the CO₂, the plume's areal extent, and its potential migration pathway after several years of injection. We also collaborate with operating companies, national labs, and other universities to create a diverse team of experts for most of our projects.



Cross section of hypothetical EOR field showing CO₂ injection zone, regional confining unit restricting CO₂ from upward movement, and overlying shallow zones containing variable sand and shale layers. Some faults offer possible migration pathways for CO₂. All these elements are carefully considered before CO₂ is injected into the reservoir.

CO₂ Storage/EOR

Dr. Mehdi Zeidouni



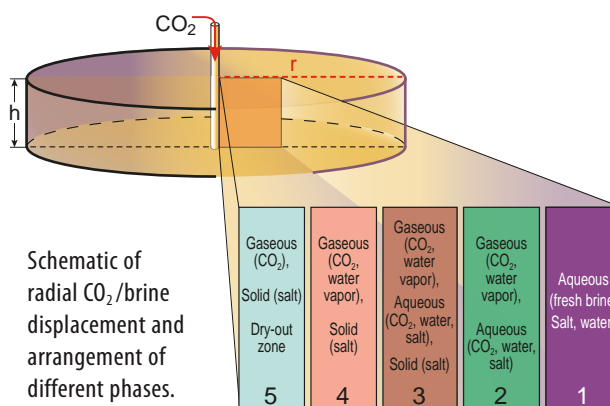
With my B.Sc. and M.Sc. degrees in petroleum engineering in hand, I started working on CO₂ storage and enhanced oil recovery (EOR) to earn my Ph.D. CO₂ storage/EOR seemed to be the solution to a global problem that I could apply while building on my petroleum reservoir engineering expertise. Then, after joining the Gulf Coast Carbon Center (GCCC) at the Bureau in December 2011, I continued working on CO₂ storage, but now focusing more on EOR. Problems with CO₂ storage/EOR, however, are much easier to identify than solve. One of the main arguments against the practicality of CO₂ geological sequestration is that it cannot be deployed safely if it is to be done at a scale required to mitigate climate change. In other words, it is argued that containment and large-scale injectivity cannot co-occur!

My research has therefore come to focus on the parameters controlling both injectivity and containment of CO₂. For injectivity, I study salt dry-out and pressure build-up induced by CO₂ injection. For containment, I work on detection and characterization of leakage pathways in caprocks overlying CO₂ injection zones.

Salt dry-out is a solid-salt-precipitation phenomenon resulting from vaporization of aquifer brine by injected, dry CO₂. Salt precipitation reduces near-well-bore permeability and adversely affects injectivity. Colleagues and I have developed a model that analytically evaluates amount of salt precipitation without the need for complex three-phase numerical simulations.

When CO₂ is injected in the reservoir, it propagates much more slowly than does pressure induced by injection, and the pressure (especially in the above-zone interval) is sensitive to leakage. The pressure can therefore be used for monitoring CO₂

injection performance and leakage. Leakage can occur mainly through old, abandoned wells and/or faults, and injected CO₂ and native reservoir fluids



can leak toward the surface if they hit leaky wells and/or leaky faults. I have developed a method of detecting leakage that is based on pressure transient behavior in aquifers overlying the injection zone. So that the pressure signal might be used quantitatively, I have developed analytical models for leakage through wells and faults. Using these models, we can discover whether any leakage occurs and, if so, how severe it is. We should also be able to decide whether the leakage pathway is a fault or a well and to predict how severe the leakage can become over time.

To enable timely leakage detection, however, the pressure-monitoring network must be designed properly. I am using an inverse theory to find the optimal design, and I am currently working on other monitorable data (for example, temperature) to be used along with the pressure data for leakage detection.

"It is godlike ever to think on something beautiful and on something new."

Democritus

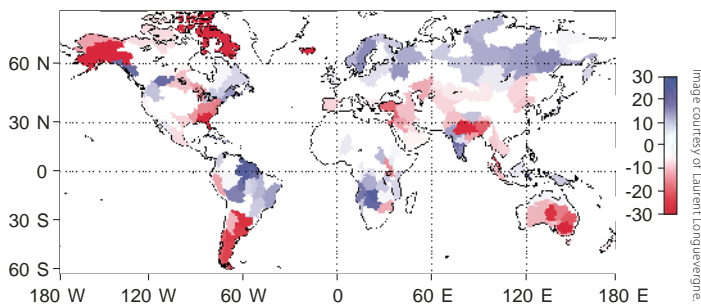
Unraveling History of Water Recorded in Soil Cores and Aquifers and Monitored by Satellites



Dr. Bridget Scanlon

Although many suggest that future generations will have several careers during their lifetime, I think we have been experiencing this phenomenon at the Bureau over the decades. When I first came to the Bureau in the late 1980's with a Ph.D. in karst hydrogeology, our first project related to site characterization for radioactive-waste disposal. This involved a shift from humid karst to arid soils, but thanks to guidance from willing soil

when we could collaborate with colleagues across the country and email manuscripts back and forth. I am grateful for the kindness of researchers in this country who helped me in those days, their openness and willingness to share their knowledge with me. We moved on to the High Plains and contamination issues near Amarillo that were attributed to waste disposal in ephemeral lakes or playas originally thought to be evaporation ponds.



Trends in water storage (mm/yr) between 2003 and 2009 showing effects of irrigation (Turkey, India), drought (SE U.S., Australia, La Platte), ice melting (Alaska, Patagonian Icefield), and permafrost effects in northern latitudes.

It was thought that tens of feet of clay beneath these playas would not allow water or waste to percolate; however, ponding water with blue food coloring showed water movement through cracks in these clays, and gravity prevailed as water and contaminants moved downward over time. Traces of tritium from bomb-pulse testing in the 1960's also provided evidence of downward water movement. More recently we have shifted to agricultural impacts on water resources, with irrigation consuming about 90 percent of global fresh-water resources. The Jackson School has changed how we do research today and has provided

support and flexibility (so that we can evaluate water-resource issues globally) and added bright, international postdocs to our group. Through Laurent Longuevergne's tenure as a postdoc and collaboration with Clark Wilson at the Department, we could look at changes in water storage globally using GRACE satellites. We now emphasize validation of satellite estimates using ground-based data in various aquifers, mostly in the U.S. in the High Plains and Central Valley aquifers, but also in the North China Plain and other systems. Although many things have changed over time at the Bureau, some things do not change—a couple being the true collaborative spirit among researchers and the wide variety of research problems to tackle.

scientists in the U.S., notably Peter Wierenga and Glendon Gee, through long phone conversations before email, we delved into this new area. Because of our naiveté, we delved into areas that trained researchers might not have taken on and discovered that water was moving upward rather than downward through the soil and that desert areas had been drying out since Pleistocene times. We learned so much from drilling and sampling soil profiles, and unraveling history recorded in these profiles was fascinating. Modeling also helped us synthesize our understanding. How funny to think that in those early days I would sometimes stay overnight to run codes to take advantage of lower computer rates, and now we can take our computers everywhere! It seemed like a miracle

support and flexibility (so that we can evaluate water-resource issues globally) and added bright, international postdocs to our group. Through Laurent Longuevergne's tenure as a postdoc and collaboration with Clark Wilson at the Department, we could look at changes in water storage globally using GRACE satellites. We now emphasize validation of satellite estimates using ground-based data in various aquifers, mostly in the U.S. in the High Plains and Central Valley aquifers, but also in the North China Plain and other systems. Although many things have changed over time at the Bureau, some things do not change—a couple being the true collaborative spirit among researchers and the wide variety of research problems to tackle.

Remote-Sensing Hydrology

Dr. Di Long



Climate change, extreme climate events (for example, droughts and floods), and intensification of human activities (land use/cover change and large-scale irrigation) have been profoundly changing the hydrological cycle and natural system in the world, and, in turn, pose increasingly critical challenges to the sustainability of water resources while economically and politically influencing society. Examining mechanisms of processes and changes in the hydrological cycle is critical to an understanding of these issues and alleviating their adverse effects on natural and human systems. Because the hydrological cycle is spatially and temporally coupled with these systems, addressing the challenges calls for an integrative, comprehensive interdisciplinary study of hydrology and water resources.

Surface-flux exchange at the interface between land and the lower atmosphere plays a fundamental role in determining the availability of water on Earth's surface and a range of ecological and climatic processes. Accurately simulating surface fluxes, especially evapotranspiration (ET), will lead to a greater understanding of these hydrological, ecological, and climatic processes across varying spatial and temporal scales, which can benefit a multitude of disciplines, including hydrology, meteorology, climatology, agriculture, forestry, and ecology. Satellite remote sensing provides an unprecedented opportunity for capturing variability in ET at a range of spatial and temporal scales. However, a series of issues (for example, inadequacies of model development and scale/scaling issues in variable retrieval)

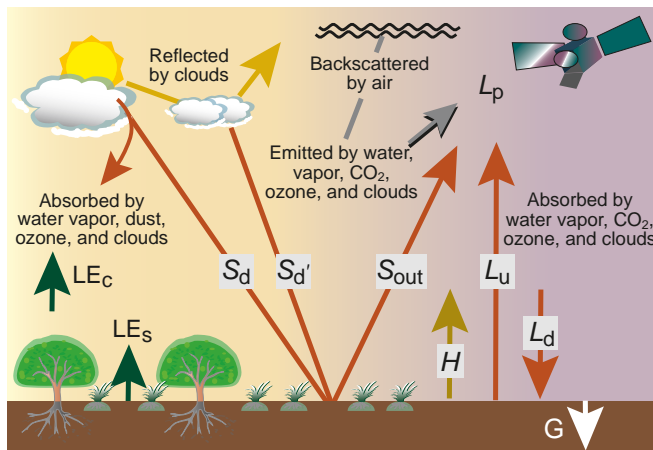
must be addressed for the exponentially increased satellite observations to be fully realized. Addressing these issues is crucial to an elevated understanding of the interactions between variability in the hydro-

logical cycle, climate, energy, and ecosystems, as well as to use of information on water fluxes for water-resource management, flood/drought monitoring, forest management, etc.

In general, my research focuses on improving the simulation of hydrological-state variables and heat-flux exchanges between land surface and the atmosphere at variable spatial and temporal scales

using remote sensing, placing particular emphasis on estimation of radiation, ET, and groundwater-storage change using satellite data—MODIS, Landsat, and GRACE. Two important issues are specifically interrelated in these areas: (1) physical and mathematical description of radiative and turbulent heat fluxes, including model development, validation, and application, and (2) scale/scaling issues in variable retrieval and model development.

At the Bureau I work as a Postdoctoral Fellow, making use of my solid background in earth science, advanced mathematics, statistics, entropy theory, remote sensing, GIS, and modeling of hydrological flux and state variables. My postdoctoral research on satellite-based groundwater and soil-moisture modeling affords me the opportunity of enhancing my understanding of satellite-based approaches for hydrological modeling, resulting in unique contributions to the hydrological and remote-sensing communities.



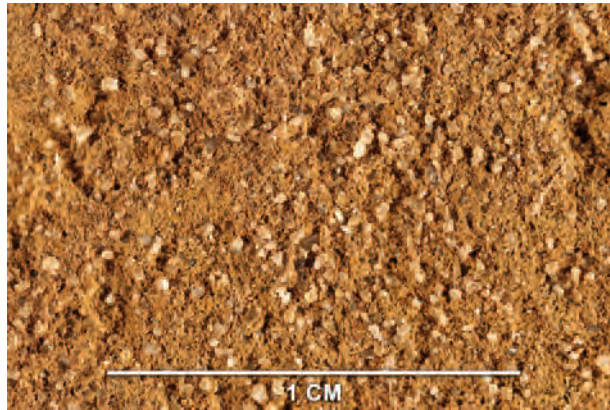
GRACE twin satellites for detecting variations in Earth's gravity field and terrestrial water-storage change.

Secret Groundwater Movement Is No More



Dr. J.-P. Nicot

Few stop to consider the ramifications of having water readily available at the tap or of the work required to ensure a constant supply of this seemingly inexhaustible commodity. Although crucial to daily life, however, tap water is hardly our only use for water—we require more to grow crops, generate electricity, and produce goods. Groundwater science has made significant progress since 1904 when the Texas Supreme Court declared that “...the existence, origin, movement, and course of such waters, and the causes which govern and direct their movements, are so secret, occult, and concealed...” and instituted the rule of capture—still valid today. Although groundwater is hidden from view and its movement characterized as complex, hydrogeologists currently have tools at their disposal to negate this statement. One is the considerable data recorded in the past 50 years on aquifers and subsurface geology. Such data, combined with a thorough understanding of the physical principles of flow in porous rocks, have made numerical modeling unavoidable in current groundwater analysis. Numerical models are often used to predict future aquifer behavior and its interactions with surface water such as springs, rivers, and lakes. Accuracy of the projections depends on the quality of the data that can be collected. Hydrogeologists at the Bureau and I spend much of our time collecting data in the field or from other sources, ensuring that the dataset is internally consistent and of size and quality sufficient to meet research objectives.



Carrizo sandstone, Carrizo aquifer host; hand sample collected at City of San Antonio Aquifer Storage and Recovery facility, Bexar County, Texas.

Armed with models, we hydrogeologists can then grasp, for example, the impact through time of a new well field on a neighboring well field or on local rivers and springs or the impact of droughts of various intensity and duration on a groundwater resource. We can also estimate fate and transport of natural and human-made contaminants or assess the annual

amount of water available for withdrawal. In all cases, hydrogeologists play the crucial role of informing policymakers and other stakeholders about water issues. New technical developments, such as the recent jump in oil and gas production owing to water-consuming hydraulic-fracturing techniques or the storing of water underground instead of in surface reservoirs, have also required input from hydrogeologists.

The frontier currently being investigated by Bureau hydrogeologists is brackish groundwater. As fresh groundwater resources are depleted or tied up, industry and municipalities are moving to the next-best thing, slightly saline water. More complex numerical models accounting for density differences due to salinity differences are then needed to evaluate the feasibility of developing these generally deeper aquifers. An immense data-collection push by Bureau hydrogeologists is in its early stages, and questions similar to the ones that we asked about fresh-water aquifers might be answered. This collection will allow us to optimize use of eventually limited water resources and to develop a drought-resilient water strategy in Texas.

Water You Doing?

Bob Reedy



Water is necessary for life itself. Usable fresh water is integral to almost every aspect of daily human activity, yet accounts for only about 1 percent of the Earth's total water. We rely on water, sometimes in humanly vast quantities, as a fundamental requirement of our food, mining, energy resource, and thermoelectric power-generation industries. Most of us are not aware, however, of how much water we really use. For instance, you may be surprised to learn how little food 1,000 gallons of water will produce: a single 1/3-lb hamburger, one gallon of milk, or 10 pounds of corn. By comparison, that same 1,000 gallons of water is all that is consumed in generating about 2 months of electricity for the average U.S. household. Yet again, that amount of water would cover the average U.S. suburban lawn to a depth of only 1/4 inch.

As a hydrogeologist working with a team of other environmental scientists at the Bureau, I focus my research primarily on how human activities and demands impact the water cycle. For example, one of the main aspects of my work has been to quantify the amounts of recharge that different aquifers receive and how that recharge may be changing over time as a result of agricultural activity. Although our projects are funded primarily by State and Federal agencies and organizations with fairly specific research goals, our research addresses issues that are of both basic and general interest to the field.

We use many different and often concurrent approaches in our investigations. For some



studies, we collect environmental samples, including water, soil, and vegetation to be analyzed for different chemical and physical properties. I often spend several weeks per year in the field collecting samples and/or conducting field experiments. We have our own laboratory facilities for many of the different types of sample analyses that we require.

Other studies may require deployment of automated sensors and monitoring equipment so that we may observe and measure environmental changes through time. I have deployed several such installations, some of which have now been in continuous operation for 12 years. In addition to these more traditional "hands-on" methods, we are also now utilizing and integrating into our studies more recently developed remote-sensing methods that are based on satellite imagery and other space-based sensor data.

Another broad and useful class of tools that we frequently employ includes computer-based models that mathematically mimic real-world chemical and physical processes. These models can provide insight and guidance in addressing questions of concern—for instance, in estimating how the amount of water stored in an aquifer might change in response to climate variability or to an increase in pumping. It is important that we particularly understand human impacts on the water cycle so that we may make informed, reasonable, and responsible decisions concerning how we manage our water resources. Do you know where your water comes from?

Finding Solutions in a World of Uncertainty

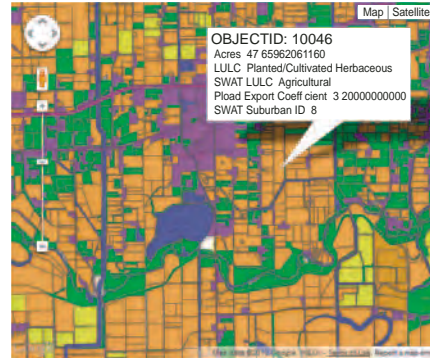


Dr. Alexander Sun

My main research areas are in water-resources management and decision support. In particular, I am interested in addressing the following questions: how to leverage scientific research for sustainable water resources management, how to support environmental decision-making under knowledge and linguistic uncertainty, and how to create two-way communication between decision-makers and stakeholders. Although there are no black-and-white answers to these questions, a multidisciplinary approach clearly must be taken, one that requires strong persistence, enthusiasm, and creativity.

We live in a world of uncertainty. A plethora of examples exist in water resources and geoscience, where there is uncertainty associated with the timing and amount of available water supplies, locations of contaminant plumes, and the structure of subsurface formations. As a hydrologist, I have worked on two major facets of environmental decision-making: uncertainty quantification and risk assessment. The former refers to the process of quantifying the impact of knowledge gaps on prediction using statistical and stochastic tools,

Watershed LULC Map

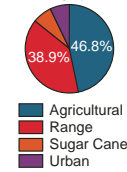


Total Nitrogen Loading [kg/yr]

Total: 762,680

Subbasin	Total Nitrogen Loading [kg/yr]
1: 32664	
2: 24312	
3: 27291	
4: 62026	
5: 21595	
6: 34811	
7: 39001	
8: 51564	
9: 19085	
10: 26594	
11: 33013	
12: 202022	
13: 25202	
14: 19787	
15: 84174	
16: 24999	
17: 34542	

Loading by LULC



A web-based nutrient-transport modeling system that is implemented using Google cloud-computing services. It provides a common platform for collaborators to interact with one another while performing nutrient-loading scenario analyses.

design, development, and deployment of a useful decision support system can be rife with challenges, not only because of the constantly changing technology, but also because of the changing water-management paradigm and perception of the public. Over the years, I have been fortunate to work on a number of projects related to high-level radioactive-waste repository, geologic carbon sequestration, and watershed nutrient-load reduction, all of which have involved a significant uncertainty-analysis component. On a recent project, I applied visual analytics and cloud-computing technologies to facilitate online collaborative decision-making and web-based model-uncertainty analysis.

At the Bureau, I work as a member of both the Gulf Coast Carbon Center and the hydrology group.

whereas the latter refers to the process of transforming outputs of uncertainty analysis into a form usable by decision-makers and the public. Environmental decision-making problems are semistructured and often cannot be defined unambiguously using a single set of criteria. Thus, the

Sustainable Water-Resource Management



Dr. Brad Wolaver

As a Research Associate at the Bureau, I focus my research on sustainable water-resource management for people and the environment, particularly in semiarid and arid regions. I enjoy working on broad research questions, such as (1) What are the most effective water-management strategies for important energy and power sectors? (2) How can we sustainably use limited water resources, especially

as population continues to grow? (3) Because groundwater is intrinsically linked to surface water, what are the best ways to develop these water resources—and what are the economic implications of these choices?

My research integrates existing programs at the Bureau and UT. For example, I am part of the Bureau's Sustainable Water Resources Program led by Bridget Scanlon, in which we investigate better ways to use water in Texas, including storing water underground in aquifers and recovering and desalinating brackish groundwater. We are also collaborating with economists and biologists to explain economic impacts of changes in water use to preserve river habitat of aquatic species that may be added to the Endangered Species Act. In my research I engage students whenever possible, including a summer undergraduate intern in 2012, as well as guiding the research of two current graduate students. In addition, I work extensively



How might we have to use water differently if aquatic species are listed as endangered or threatened? What could the economic effects of these changes in water use be? A current project seeks to explain the economics of keeping water in rivers to preserve aquatic habitat for endangered or threatened species, including five species of freshwater mussel found throughout central Texas that may be included in the Endangered Species Act in the future.

with researchers in the Gulf Coast Carbon Center, in which we develop groundwater-monitoring techniques for Gulf Coast oil fields undergoing enhanced oil recovery (EOR), with CO₂ being captured at power plants and other industrial sites. Our research helps put CO₂ underground that would have otherwise been released to the atmosphere—and increases domestic energy security by increasing production at proven oil fields. In the larger Jackson School, my research overlaps with research

themes in Climate, Carbon, & Geobiology, as well as Surface & Hydrologic Processes.

Although I grew up in Austin and originally became interested in geology and water resources while hiking on the Barton Creek Greenbelt, I have been fortunate to work in some unique parts of the world. These experiences help make me, in turn, a unique research contributor at the Bureau. As such, I draw upon my background in both applied groundwater resource management from my years of working as a practicing professional hydrogeologist figuring out how to best manage limited water for 20 million people in Southern California, as well as my extensive field hydrogeology research experience in the United States, Australia, Chile, and Mexico. In the future, I look forward to continuing to explore and learn how to best manage limited water resources as a researcher here at the Bureau.

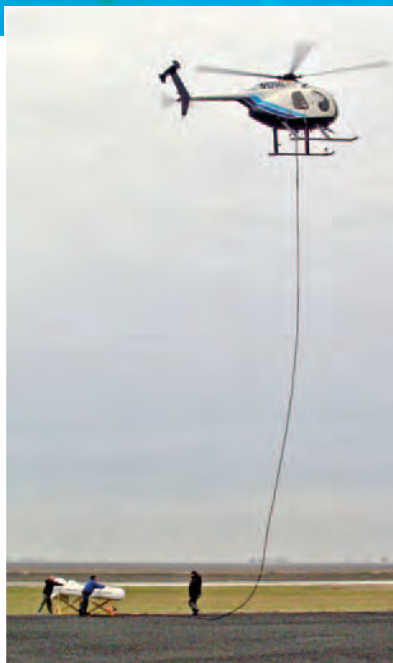
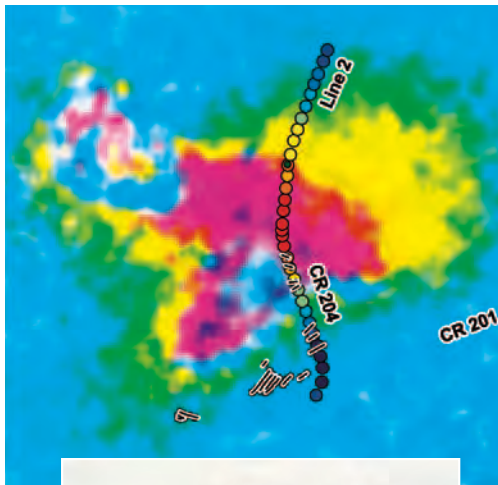


Observing the Earth beneath Our Feet

Dr. Jeffrey G. Paine

Sometimes it is a challenge to find a common theme in sponsored research that spans decades, geographic extent, and the ebb and flow of societally relevant topics in earth science. For me, the unifying theme of my career is the study of the strata just below us: the realm of the surface and near-surface. Much of our interaction with our planet is within this realm, and many examples illustrate its importance to people, plants, and animals. Surficial deposits that produce our food and support our homes, roads, and businesses are disproportionately impacted by modern geologic processes such as hurricanes, floods, faulting, subsidence, and sea level. Natural and human-caused salinization of surface and near-surface deposits affects land use, wildlife, and surface-water and groundwater supplies. Dissolution of evaporite deposits and collapse of overlying strata form sinkholes in west and central Texas and on the coastal plain, threatening public safety and public and private infrastructure.

At the Bureau, we employ a diverse set of surface, borehole, and airborne instruments as part of our "Near-Surface Observatory." Fundamental advances in our understanding of our planet's skin are made as we explore the applications and test the limits of each instrument, analogous to advances in particle physics (with bigger and better accelerators) and in astronomy (with more powerful telescopes). Each



geophysical or imaging tool reveals a unique aspect of the surface and near-surface. Shallow seismic reflection and ground-penetrating radar methods illuminate near-surface geologic structure and stratal configurations that allow us to detect ancient river courses or past movement across faults. Electromagnetic-induction instruments respond to changes in mineral makeup, water content, and pore-water chemistry that are critical parameters for characterizing aquifers and delineating the impact of salinization. Airborne laser mapping (lidar), pioneered at the Bureau for coastal applications such as shoreline change and storm impact, has been expanded to include bathymetric and hyperspectral imaging capabilities. These enhancements are allowing us to evaluate new approaches to characterizing coastal wetlands and promise to enable significant advances in our understanding of our dynamic coast as it responds to the four S's: storms, sediment supply, sea level, and subsidence. Threats of sinkhole formation are being evaluated using satellite-based radar interferometry to monitor subsidence over the Permian Basin and guide field measurements of the local gravitational field caused by subsurface voids. Happily, we've only scratched the surface of the endless possibilities and challenges that the Earth's surface provides for us.

Soil and Water Do Much More than Make Mud

Dr. Todd Caldwell



Rock breaks down into smaller and smaller pieces and eventually becomes soil. The soil we see today is the product of climate, biology, topography,

challenge facing earth scientists today partly because our measurements are hampered by instrument limitations and natural variability. My

research focuses on both issues by first improving instrument applications to extreme environments and then using fine-scale measurements to infer larger-scale variability. In particular, I use soil development at geologic time scales to investigate ecosystem response to changing climate and rapid soil changes following a disturbance to detect and defeat improvised explosive devices (IED's) through geophysical characterization. Soil's misplaced cousins, dirt and dust, are the result of soil disturbance and erosion which are another pursuit of



Fine-scale measurements of infiltration capacity around a shrub in the Mojave Desert.

and, most important, time. As a geologist, I exploit these relationships to help decipher past climates and determine landscape dynamics. As an ecohydrologist, I use relationships between soil and plant communities to infer water resources and evaporation rates. Soil is an evolving organism with its own personality and temper that can affect our lives in both subtle and dramatic ways.

Soil ultimately controls the vertical flux of moisture by partitioning rainfall into runoff, infiltration, evapotranspiration, and groundwater recharge. The transfer of knowledge between different spatial and temporal scales is a significant

mine. Finally, I have been developing an approach to improving surface-runoff predictions using a combination of field methods, geomorphic mapping, and scaling approaches.

Soils contain a wealth of climate information, and their chemistry and particle size are results of ever-changing climate and water flux. Soil science, although deeply rooted in agriculture, has a much greater role to play in geology, ecology, engineering, and atmospheric sciences across Texas. I am a recent addition to the Bureau and Texas, and I am eager to dig into the Texas landscape!



The Coastal Classroom

Tiffany Caudle

Coastal geoscientists at the Bureau (myself included!) strongly believe that we have an obligation to support enhanced education programs and to provide information to the public. Science and society benefit when scientists reach out and engage the public and future scientists in the discovery process. Coastal processes, beach/dune systems, and public issues provide an ideal venue for teaching middle and high school students basic and applied science and for illustrating the role that science and good data-collection practices play in making public-policy decisions.

The Texas High School Coastal Monitoring

Program (THSCMP) is an ongoing Bureau project designed to help coastal communities develop a better understanding of dune and beach dynamics on the Texas coast. My colleagues and I work with middle and high school students and teachers, showing them how to measure topography, map vegetation lines and shorelines with Global Positioning Systems (GPS), and observe weather and wave conditions. As participants in an actual research project, the students provide their coastal communities with valuable data on their changing shoreline.

We work with a wide range of students: from middle to high school, from special needs to advanced placement, urban to rural. Each group brings its own challenges but also its own rewards. It isn't every day you go on a field trip to the beach! The students all actively participate in the data-collection process. Everyone has a chance to participate in all aspects of THSCMP by rotating



through the data-collection procedures. Of course there are always exceptions (mosquitoes, hot temperatures, snakes!), but at the end of the trip, I know that they have enjoyed their day spent away from the classroom and have actually learned something new about their environment.

THSCMP is a unique educational program in that the students collect data in a real-world setting that are used by working scientists to address coastal issues. We emphasize to the students that they are working on a real research project and are collecting scientifically valid data that may eventually appear in a

scientific publication or be used to create public policy. This is a major point that makes THSCMP different from most other field trips or laboratory exercises. Asking students to conduct experiments that have real consequences seems to make a difference to them, and it improves the quality of the data.

Benefits from this project accrue to the coastal public, who are directly affected by beach erosion and beach-erosion public policy. Data from this project are accessible through the THSCMP website, project reports, and scientific-journal articles.

Since 2000 I have been involved in projects that study shoreline change, coastal processes, severe storm effects and beach recovery, and tidal-inlet morphodynamics. I am proud to say that I am the coordinator for the Texas High School Coastal Monitoring Program and an instructor for the Jackson School of Geosciences GeoFORCE Texas program.

Monitoring Mangrove in the Coastal Bend

Tom Tremblay



Wetlands are an essential component of the coastal environment, providing one of the highest flourishes of biological production to be found in natural ecosystems. This fact was evident to Bureau scientists in the decade of the 1970's, when the landmark *Environmental Geologic Atlas of Texas* (Brown and others) was published, which was followed in the 1980's by the equally well received *Submerged Lands of Texas* (White and others). Both series highlight natural environments and contain detailed wetland maps of the Texas coast. In 1993, I coauthored the Galveston Bay National Estuary Program wetlands status and trends report. Later that decade, I coauthored a similar report for the Corpus Christi Bay National Estuary Program. With the new millennium, my colleagues and I have embarked on a coastwide wetland status and trends study, starting with the barrier-island system. By 2012, we had completed the wetland status and trends studies for most of the Texas coast. Of utmost concern has been the effect that climate change has on coastal environments, specifically wetlands—we encounter climate-change effects in the form of relative-sea-level rise and global sea-level rise + subsidence. The coastal bend is a good example of where habitat changes have occurred as a result of climate change. As temperature increases, habitats shift farther northward, and



relative-sea-level rise compounds the effect of climate change when habitats move farther inland as the land experiences more frequent flooding. Marshes and mangroves, for example, spread into slightly higher flats. Tidal-flat land is a necessary component of the wetland system because flats facilitate nutrient cycling into bays and provide food and shelter to wildlife. Although mangroves are considered a threat to marsh habitat at Aransas National Wildlife Refuge, without freezes to cull the population, mangrove grow to a height sufficient to provide cover for whooping crane predators. I have therefore proposed a study to monitor the movement of mangrove along the Texas Coastal Bend. Climate change, in conjunction with human modification of the barrier-island system, will alter the vegetation composition of the coastal-bay system. Wetland habitat studies will help us understand the effects of climate change in coastal environments and provide a detailed base for further studies.



GIS and Its Wide Variety of Uses

Ruth Costley

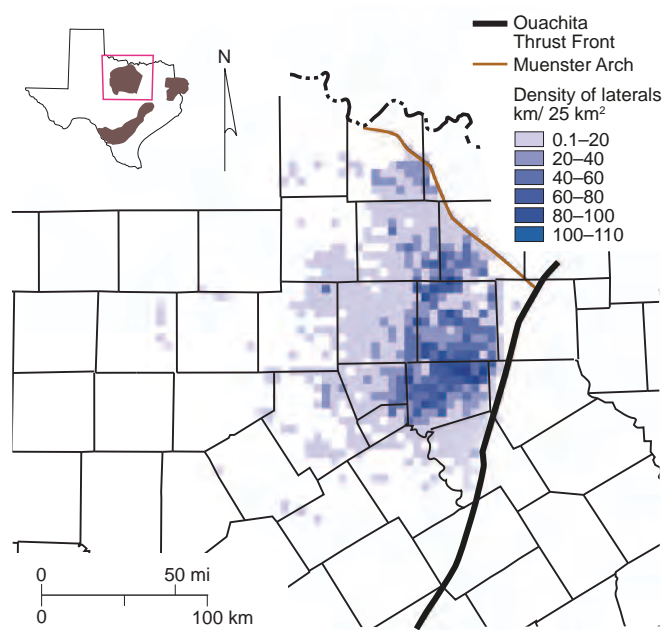
GIS is a powerful technology and research tool that has a wide variety of uses. People use it every day for tasks such as finding the quickest route to a destination or locating their perfect house in close proximity to schools. As a GIS analyst at the Bureau, I have been able to apply GIS to a wide variety of projects.

First, I have recently been using GIS to look at the spatial distribution of oil and gas wells. For the oil field in Cranfield, Mississippi, I was asked to map the spatial distribution of these wells. Then, so that the wells could be better understood through history, I was able to create animations for the cumulative oil, gas, and water production over time. This task was easy using the Animation Toolbar in ArcGIS software. In addition, for shale formations across Texas, I have mapped the density and water intensity of injection wells for given plays, such as the hydraulically fractured horizontal wells of the Barnett Shale.

I have also used GIS to evaluate water resources in a particular area. For one project, I helped build a GIS database for north-central Texas to evaluate and attempt to quantify the water resources available for hydraulic fracturing. The potential water

sources included both groundwater and surface water not allocated for human consumption. The database collected for groundwater modeling

included structure, net sand thickness, and hydraulic conductivity of the subsurface. For surface waters, Landsat satellite images were classified to identify water. Area and volume of water could then be calculated from the resulting polygons. Similarly, I helped to collect a GIS database for Brown County, Texas, which needed to find places to drill water wells. We again built a database that included structure and salinity.



Density of horizontal wells in the Barnett Shale Formation.

For other projects, I have helped make maps of study areas to be used in reports or in the field. For the Environmentally Friendly Drilling Project, which is a program to develop technologies to reduce the environmental impact of drilling, I have been creating a wide variety of maps from publicly available data, including mean temperature, mean precipitation, land cover and land use, and U.S. Census data. Of course these are just a few examples. I really enjoy the versatile use of GIS here at the Bureau.

How Can We Better Manage Water Resources?

Dr. Hui Wang



As a Postdoctoral Fellow at the Bureau, my research focuses on sustainable water-resource management, water-infrastructure security analysis, and the water-energy-environment nexus using statistical methods, system-uncertainty analysis, and risk-assessment methods.

In sustainable water-resource management, I have worked on various problems, including climate-information-based precipitation/streamflow forecasts, multipurpose reservoir operation while incorporating ecological-flow requirements, and impact of climate change on water resources at watershed scale.

Accurate medium-range precipitation forecasts are critical to water-resource planning and management. To improve 15-day-ahead accumulated-precipitation forecasts, I have developed a combination scheme to integrate reforecasts from a numerical weather model and have disaggregated precipitation forecasts from a climate model. At the same time, operational streamflow forecasting is also important for water utilities to manage water resources such as irrigation and hydropower generation. Although deterministic streamflow forecasts have been utilized extensively in research and practice, ensemble streamflow forecasts and probabilistic information are gaining more attention. My contribution in this area has involved developing a multivariate linear Bayesian regression approach so as to provide probabilistic streamflow forecasts by incorporating gridded precipitation forecasts from climate models and lagged monthly streamflow data. One common effect of regulated releases from a reservoir is induced change in



Philpott Dam, Virginia—study site for revising reservoir operation to incorporate ecological-flow requirements.

Photo courtesy of <https://thesacadahighland.wordpress.com/2010/07/22/philpott-dam-lake-in-virginia/>.

the hydrologic-flow regime that potentially impairs the aquatic environment by altering natural-flow conditions. Most reservoir operators consider downstream environmental flow as a constraint to meet a minimum release. For a better solution, I have proposed

an adaptive reservoir-operation framework to explicitly incorporate ecological-flow requirements, which can be adapted to daily streamflow predictions.

Concerning water-infrastructure safety, a reliable and safe water supply depends on reservoirs that balance temporal and spatial variation in quantity of water resources and reliability of water-distribution networks. My past work (for example, accidental/intentional contaminant characteristics in water-distribution networks and groundwater, integrated risk assessment of leakage in water-distribution networks) reflects my research interests and studies in water-infrastructure safety. Previous research experience has extended my interest in examining safety issues in water infrastructure, including large dams and water-distribution networks in a broad context.

Regarding the water-energy-environment nexus, a substantial amount of water is withdrawn or consumed in energy production—for example, hydropower generation and shale-gas drilling. Environmental risks are also associated with energy production—for example, potential air and groundwater pollution from shale-gas development. I am currently conducting research in this emerging area with Dr. Ian Duncan.

Implications for Biofuel Production



Dr. Xianli Xu

The Midwest region of the United States is an important area for the production of first-generation biofuels. From 2009 through 2011, the Midwest accounted for 80 to 90 percent of U.S. corn and soybean production. However, potential adverse impacts of biofuel production on water resources are a concern.

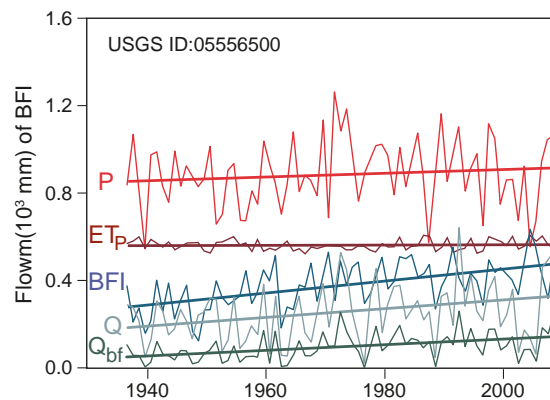
I am a Postdoctoral Fellow at the Bureau. My study focuses mainly on impacts of land use and climate change on soil and the hydrology cycle. One focus of my research

has been to assess the potential impacts of biofuel production on water resources. I have been exploring impacts of climate and land-use change on the hydrology cycle on the basis of long-term (from the 1930's through 2010) stream-gage and climate data from 55 unregulated watersheds in the Midwest. I have evaluated long-term trends in both climate (precipitation and potential evapotranspiration) and flow. My research group at the Bureau and I have recently examined the sensitivity of changes in annual streamflow and baseflow to climate using a climate elasticity (sensitivity) method, and the residuals were attributed to land-surface changes. Results show that streamflow increased significantly ($p < 0.05$) in 36 percent (20/55) of watersheds

(median 2.3 ± 0.4 mm/yr), baseflow increased in 65 percent of watersheds (median 1.0 ± 0.4 mm/yr),

and baseflow index (baseflow/streamflow, BFI) increased in 44 percent of watersheds (median $0.2 \pm 0.1\%/yr$). Overall, land-surface change and climatic variability contributed similarly to streamflow change ($56 \pm 16\%$ vs. $46 \pm 16\%$), whereas land-surface changes contributed much more to baseflow ($78 \pm 9\%$ vs. $22 \pm 9\%$; 3.5 times higher) and to BFI ($109 \pm 11\%$ vs. $16 \pm 13\%$; 6.8 times higher) than did

climate change. Watersheds (25/55, 45%) having no significant trend in climate but having significant flow trends provided direct evidence that Midwest land-surface change (including cropping systems and related land-management practices) significantly impacted flow processes. Restricting analysis to these watersheds showed that land-surface change contributed 3.0 times more than climate variability/change to streamflow change, 4.6 times more to baseflow change, and 13.5 times more to BFI change. The importance of past land surface changes on hydrology suggests that any future land-surface changes, such as biofuel expansion or changing biofuel feedstocks, should consider impacts on regional hydrology. These and other exciting investigations at the Bureau keep my life interesting!



Case gage (watershed) with no significant climate change but with significant hydrologic change.

Risky Business

Dr. Ian Duncan



My research is focused on understanding risks to the environment of energy extraction. Assessment of these risks and how they might be mitigated is crucial to providing the public and other stakeholders with confidence that energy extraction can be done in an environmentally sound manner. I am working in two main areas of interest: (1) an understanding of the risks associated with future CO₂ sequestration projects and (2) an evaluation of the environmental and health risks associated with extraction of shale gas by hydraulic fracturing. Studies have shown consistently that the general public and even scientific experts have an understanding of the relative magnitude of risk that differs strongly from a dispassionate evaluation of relevant facts. Partly because environmental risks have a strong emotional component with many, how scientists communicate risks to the public can be as important as their understanding of the nature and magnitude of the risks.

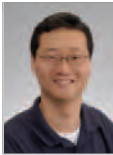
Risk assessment of a geologic CO₂ sequestration project involves identifying hazards, assessing the likelihood or probability of damages arising from the hazards, assessing the range of severity of damages (or consequences), and combining assessments of likelihood and severity of consequences—all to produce an assessment of risk. Owing to a lack of a large historical dataset (because CO₂ sequestration is a new technology), assessment of long-term risks associated with CO₂ sequestration is difficult. The approach being taken by my research group is to evaluate the worst-case-scenario consequences for all plausible risk scenarios for specific sequestration tasks. The risk



can never be worse than the worst consequence. For example, if no valuable groundwater resources exist near a sequestration site, the risk to groundwater quality is inherently limited. We are developing a comprehensive set of scenarios so as to model the likelihood of accidents using probability estimates from analogous activities. My research group and I are examining three aspects of risk: (1) leakage and accidents associated with CO₂ pipelines, (2) blowouts of CO₂ injection wells, and (3) subsurface leakage from CO₂ injection wells as a result of well-bore

integrity problems. We are developing a numerical modeling approach that is based on combining Bayesian Inference, Markov Chain, and Monte Carlo simulation.

Leakage from shale-gas wells has potential environmental and health impacts, including contamination of ambient air and groundwater. Compared with that of conventional natural gas drilling, shale-gas extraction has a relatively short history and information about it is limited. My current research includes (1) evaluating the health risks associated with shale-gas operations via airborne exposure pathways, (2) coming to an understanding of the nature and magnitude of methane emissions from shale-gas operations, (3) investigating the origin of stray methane gas spatially associated with shale-gas plays, (4) evaluating the nature and risk of subsurface blowouts associated with shale-gas production, and (5) evaluating the risk of potential groundwater contamination associated with shale-gas extraction activities.



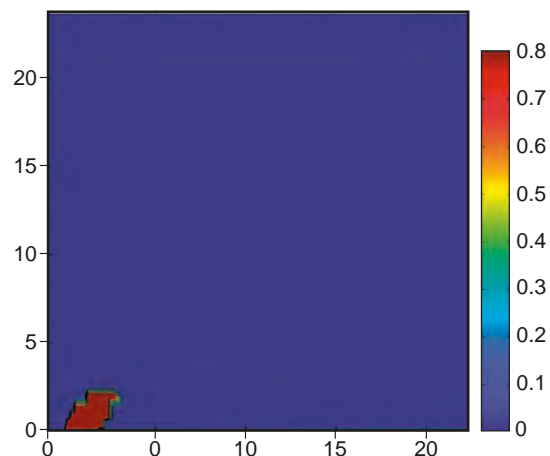
Geomechanics for the Environment and Energy Production

Dr. Jong Won Choi

Geological carbon sequestration involves the injection of large volumes of CO₂ into reservoirs or saline aquifers, leading to development of overpressure over initial pressure, which, in turn, causes a change in the stress field around the injection wells. That is, because of increased pore pressure, effective stress is changed even if total stress remains constant. This change in stress field may create problems, such as fault reactivation, triggering of earthquakes in critically stressed regions, and failure of caprocks.

Hence, an understanding of the variation in stress fields in response to pore-pressure change is crucial to the success of geological carbon sequestration. Current models are based on rather simplified assumptions, such as plane-strain conditions or reservoirs/aquifers in a semiinfinite medium. Considering the depth to typical reservoirs/aquifers for sequestration, the existence of the mantle, which is softer than the Earth's crust, may need to be considered. Accordingly, a two-layer model—a hard layer (Earth's crust) over a soft layer (mantle)—would be advantageous for addressing realistic boundary conditions.

On the other hand, shale gas has recently emerged as a potential major energy source in the United States. This gas has been classified as an *unconventional gas*, which means that permeability of the reservoir rock is low. Hence, stimulation, such as hydraulic fracturing, is essential to attaining economical production rates.



Quarter crack on an x-y plane. Note failed region around crack, which is due to applied pressure on the crack surface. Blue region represents intact material, whereas red region designates failed zone, which is due to locally developed tensile stress. This failed zone suggests development of microcracks around cracks that result from hydraulic fracturing.

Although considerable effort has been expended in investigating the large-scale propagation of hydraulic fractures, the role of microscale fracturing has been largely ignored. Gas shales are fine-grained rocks that have significant rheological heterogeneity at the micron scale. Quartz- or calcite-dominated regions are brittle elastic, and clay/organic-dominated regions are plastic and bituminous lumps that are likely to behave in a viscoelastic manner. Such heterogeneities will respond in a complex way when they are deformed

by hydraulic fractures, resulting in generation of internal stress concentrations at the small-scale boundaries between the different rheologies. These stresses can result in microcracking, which may be a key mechanism of gas production from low-permeability gas shales.

I have been working as a Postdoctoral Fellow for the Bureau, developing numerical models so that the mechanisms of carbon sequestration in conjunction with the Southeast Regional Carbon Sequestration Partnerships (SECARB) could be better understood by simulating the CO₂ injection process and analyzing behaviors of the CO₂ plume and response of reservoirs. Currently I am working on development of a two-layer model for stress-field change due to geological carbon sequestration. I am also investigating whether and how rheological heterogeneity in gas shales can result in development and propagation of microcracks.

CCS Risk and Optimization Management

Dr. Xiaodong Zhang



Energy industries release large amounts of carbon dioxide, a major greenhouse gas that has contributed significantly to global climate change. CO₂ capture and sequestration (CCS) is an effective means of reducing CO₂ emissions to the atmosphere through storage of CO₂ in the subsurface for a long time. Although CCS provides a

good method of mitigating CO₂ emissions, it is associated with concerns about long-term storage—what are the risks of CO₂ leakage in the future? How serious could these risks be? How can the impacts on groundwater and the surrounding eco-environment be assessed? For effective answers to such questions, important tools are needed for assessing risk in CCS. I am working on these crucial questions concerning impacts and/or risks of potential CO₂ leakage during CCS, especially in the storage of CO₂ in deep brine formations and in hydraulic-fracturing processes. Major breakthroughs in my work have focused on provision of an effective risk-assessment approach, as well as tools for evaluating the possibility of potential CO₂ leakage and its impacts. Important leakage mechanisms, pathways, and receptors in subsurface reservoirs are being identified, corresponding risk-assessment tools are being developed on the basis of natural and industrial analogs, and potential impacts on underground drinking-water sources, ecosystems, and energy-resource quality are being analyzed.

CCS involves a number of components, such as multiple potential emission sources, multiple capture technologies, and multiple possible storage sites. Relevant decisions should also



Monitoring and analyzing water quality.

Photo courtesy of Renfei Liao.

consider preferences of various stakeholders and decision-makers. There are tradeoffs among economic objectives, environmental impacts, and technical considerations. How to effectively manage such a complicated system involving a number of social, economic, environmental, and

political factors is challenging for decision-makers and other authorities. Using an entire-system approach, I am currently working on development of innovative systems-analysis approaches for optimization of the CCS management system. The uncertainty about system parameters and behaviors is also incorporated into optimization models that my group and I are proposing by using an interval-analysis technique. Accurate reflection of uncertainty is essential to implementation of CCS practices. Such models can effectively tackle problems in CO₂-capture technology selection, optimization of CO₂ allocation, and systems-cost minimization, as well as CO₂ capture-facility capacity expansion. Optimal management strategies can be generated for CCS planning in cases where carbon-emissions trading is also being investigated. Our study will help decision-makers make better decisions and policies concerning CCS management.

My other research interests include environmental and health risk assessment, multiphase flow and transport modeling, site remediation, climate-change impact assessment and adaptation planning, water-resource and quality management, waste management, and energy and environmental systems analysis.



Geologic Mapping of Texas

Eddie Collins

Geologic maps are one of the oldest tools of the geological sciences, and since 1909, when the Bureau was founded, one of their primary purposes has been to display the state and to provide interpretive views of rock and sediment units of different ages to scientists, educators, and laypersons. Geologic maps and related charts, diagrams, and texts have economic and societal value in that they support decision-making for identifying, utilizing, and managing Earth resources. For example, geologic maps are used to identify mineral resources, to assess changes in sensitive coastal environments, to properly plan and permit construction projects, and to identify and plan for potential hazards. Mapping, a fundamental skill of all geologists, involves a range of tasks that I have been practicing since I arrived at the Bureau in 1978: reviewing and compiling previous geologic interpretations; studying and describing the physical attributes of rocks, sediments, and soils where they are exposed; studying aerial photography and subsurface data from boreholes; sometimes drilling test holes and digging auger holes for samples; and accurately compiling map interpretations.

Current geologic mapping at the Bureau involves constructing hardcopy maps and digital map datasets for parts of two broad geographic areas, the Texas Gulf Coast corridor and the north-central to south-central Texas population/transportation corridor. Maps are also being interpreted for local areas in Texas to support development and management of Texas mineral resources. Geologic maps for the Texas Gulf Coast corridor address geologic framework needs for planning and management of land use, evaluating historical changes of coastal depositional environments,



Photo courtesy of Jeff Payne

addressing erosion issues, and permitting activities related to resource development. These maps also contribute to the understanding of historic and ongoing sedimentation processes and past relative-sea-level fluctuations. Maps of the central Texas population/transportation corridor provide information on the geologic framework

of the region and are used for identification of aquifer recharge areas; characterization of attributes within aquifer strata; location and characterization of faults; information for water-management decisions regarding groundwater flow and aquifer response to pumpage and recharge; improved planning and permitting related to land-use activities such as construction, design of foundations, and siting of landfills and other waste-disposal sites; and location of construction materials and industrial sand resources.

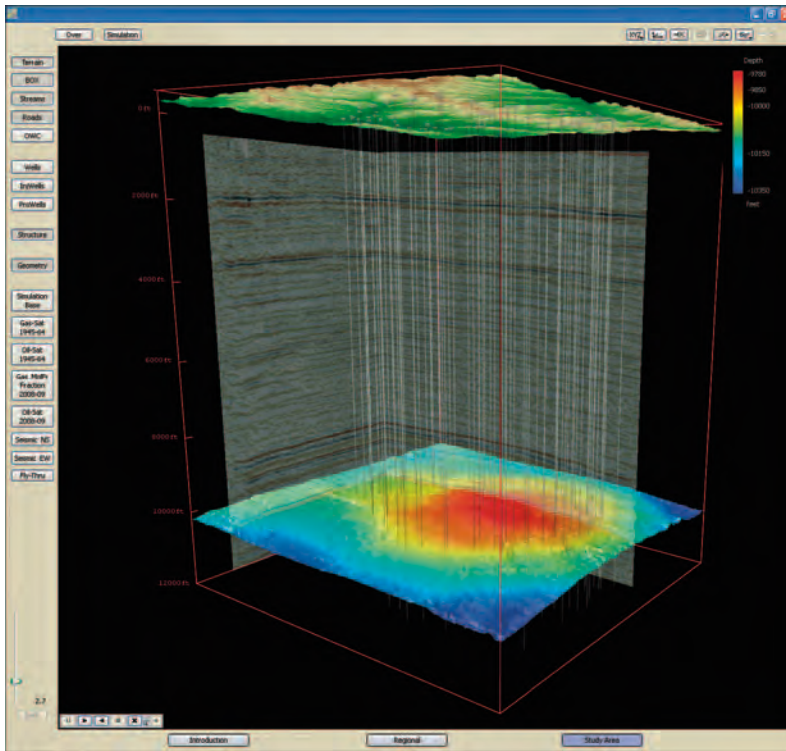
As a Research Scientist Associate at the Bureau, I coordinate two programs that involve geologic mapping of surface bedrock and surficial sediments: the Texas STATEMAP program, currently in its 20th year of activity, and the recent Mineral Resource Mapping component of the STARR project. I also coordinate a subsurface-mapping and web-based data-information site project sponsored by the Groundwater Advisory Unit of the Railroad Commission of Texas and currently in its 10th year of activity. This website, the Surface Casing Estimator site (<http://www.beg.utexas.edu/sce/index.html>), provides estimates of depths for fresh and usable-quality water, the base of underground sources of drinking water (USDW), and some geologic units related to groundwater.

21st-Century Mapping

John Andrews



Are you familiar with earth science visualization techniques? Have you ever seen geospatial information rendered in 2D? Of course you have—maps!



As a child I was captivated by maps and developed an intuitive understanding of their message at an early age, but I was later surprised to find that many folks have trouble interpreting even conventional map features, such as topographic contour lines or anthropogenic patterns in an aerial photograph or satellite image. And yet problems associated with map interpretation are compounded when the map's theme moves beyond simple land-surface characteristics to complex subsurface geological processes—movement of water through an aquifer, for example, or the presence and structure of

subsurface oil and gas traps. Unlike roads, rivers, and other features found on the Earth's surface, most geological features and concepts are inherently three dimensional—an oil-bearing rock formation, for example, has horizontal extents, which can be mapped conventionally (in 2D), but it also has depth and thickness (3D) and is generally confined above and below by other related rock formations. Given the limitations of conventional 2D mapping, how can we visualize the aforementioned scenario to improve our geological comprehension?

This and related questions are what occupy my time here at the Bureau: I work with fellow researchers to build custom software for visualizing multidimensional data. I've built projects to visualize Martian river channels, Caribbean mud volcanoes, oil fields and reservoirs here in Texas, and beach erosion and shoreline migration, also in Texas. The image reveals a typical sample of my work—

Bureau researchers collected data for a subsurface CO₂ storage study and built a numerical model to show how fluids and gasses might move through a formation—the dome-shaped feature at the bottom—when CO₂ is injected. I took the collected data—including results of the numerical model—and built an interactive 3D project to facilitate our understanding of the geology. These interactive 3D projects are particularly useful when we share our research with the public; given the complexity and/or obscurity of much of our research, a comprehensive, visual display facilitates our ability to communicate and educate.



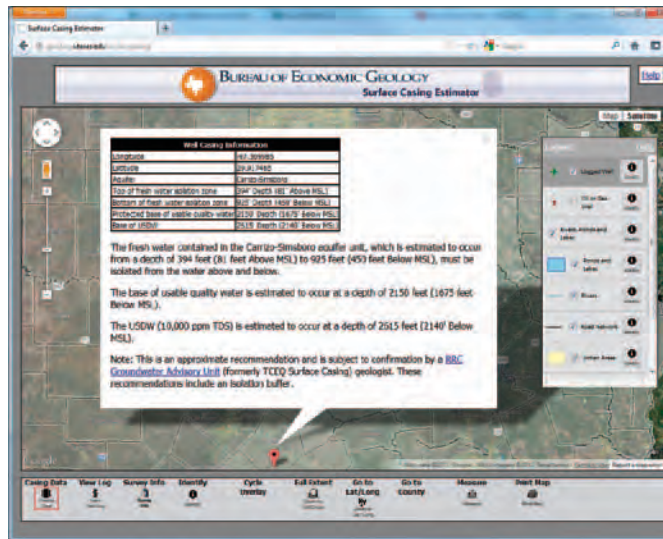
Maps in a Flash

Aaron Averett

In the past, maps were difficult to produce. They took time to draw by hand from notes or measurements taken in the field. Now, however, computer technology has made what was once an immensely difficult and time-consuming task, the actual drawing of maps, relatively easy. Computerized geographic information systems (GIS) are able to produce beautiful, precise maps in just seconds, from data that come from an array of sources. In the right hands, this awesome

speed and precision allow the user to extract and disseminate insights from volumes of data—an impossible task even a few years ago.

As a Geographic Information System Specialist with the Bureau's Information Technology Group, I develop, maintain, and operate a variety of software and hardware, primarily at the infrastructure level, that store and process geographic information. For instance, one problem that researchers frequently have is the need to present geographic data over the internet interactively. Our sponsors are generally familiar with top-flight applications such as Google Maps, and so they expect similar presentation of research results. By combining several technologies with custom code, we can reduce the task of presenting our data to a fairly simple one. Several projects



The Railroad Commission Surface Casing Estimator Site is the first web application in service at the Bureau to make use of the fusion of Google Maps with in-house data. This application assists individuals and companies applying for permits to drill oil and gas wells in Texas in determining the depth at which they need to construct a casing around their well, so as to protect the groundwater from contamination by the chemicals used during drilling. Determination of the appropriate depth is a complex process, but the application provides a friendly and familiar user interface.

within the Bureau are now making use of code that I wrote to fuse Google Maps with map data served from our ArcGIS Server over the web that has the same interactivity that users expect from Google Maps. This technique is scalable and reusable, allowing all projects that have this need to use it, thereby devoting their resources to solving scientific challenges instead of developing multiple custom web applications—a costly and difficult process.

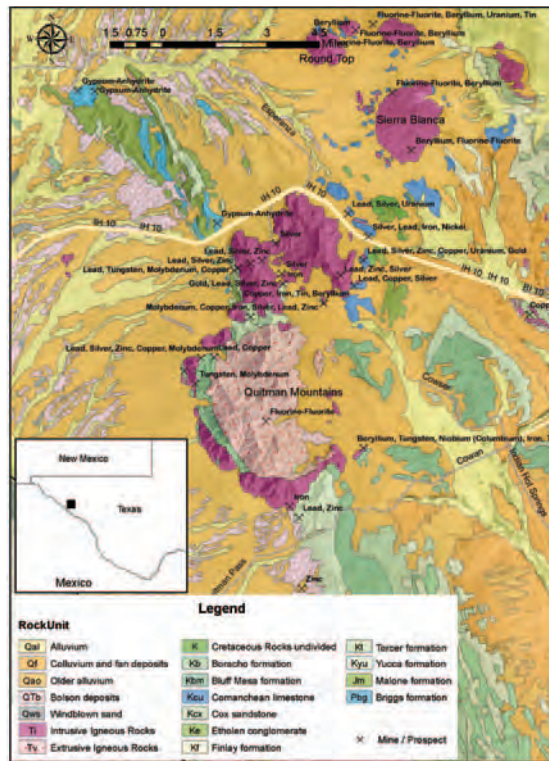
In some cases, the technical challenge our researchers face occurs at the other end of the process. Collection of some types of data requires the use of complex, computerized equipment that is difficult to operate reliably without a thorough understanding of its function. As an expert in computer technology, both GIS-related and otherwise, I assist our researchers in the field by serving as an operator and repair technician for complex computerized field equipment, such as airborne lidar and photography systems. The volume of data that these systems collect is frequently immense—simply transferring it from the instrument is often a challenge that requires the skills of an information technology expert, and in these cases, I'm the best one for the job.

High-Tech Investigative Exploration: Mineral Resources, Mapping, and Petrologic Modeling

Dr. Brent A. Elliott



As I walk the ridge line of a mountain, which is obviously a preferred wildlife route, given the well-worn path and occasional signs of their passing, I imagine my profession as a fantastic combination of Explorer Meriwether Lewis, Detective Sherlock Holmes, and a science officer from the U.S.S. Enterprise. Miles from anywhere across rugged terrain, I carry a backpack of wilderness gear and rock samples, a .44 magnum revolver holstered on one hip, an “X-ray gun” in one hand, and a 5-lb sledge hammer in the other. I pick rocks up and study them with a magnifying glass (hand lens), occasionally zapping the rocks with X-rays and reading their chemistry from the device; take measurements with a compass; record coordinates from my GPS; and make notes in a handheld computer. My mission has multiple objectives: (1) I’m looking at the chemistry of the rocks and minerals that offer clues to the history of the rock, the physical and chemical processes involved in their formation, and what resources are potentially available—Gold? Copper? Rare earth elements? Sands desirable for fracking operations? (2) I’m taking structural measurements and recording observations. I take samples for different chemical analyses, age dating, and for slicing into thin sections to observe under a microscope. I’ll use



this information to make maps and connect the rock types and structural information to regional and larger scale resource potential. (3) By gaining an understanding of the processes and sequences of events that formed these rocks and structures, I can develop a model that allows for a reconstruction of the tectonic history of the continent, magmatic and metamorphic events, episodes of mountain building, and sea-level fluctuation (for example).

My research is as diverse as the environment I work in. Whether it’s in mountains above glaciers or on desert plains, in the office or in the laboratory,

there is a resource or connection to geology that I can study—from small-scale, elemental chemistry to continental-scale tectonics, and everything in between. At the Bureau, I work with the State of Texas Advanced Resource Recovery (STARR) minerals program and the STATEMAP mapping initiative. Although these programs cover a large area and a wide range of topics, I’m particularly interested in the geochemistry and petrology of magmatic and metamorphic rocks across Texas and economic resources directly or indirectly related to these events. I am also working on mapping areas in central Texas that may have economic potential for producing sand, gravel, clay, and limestone commodities.

Using Light Beams as an Information Source



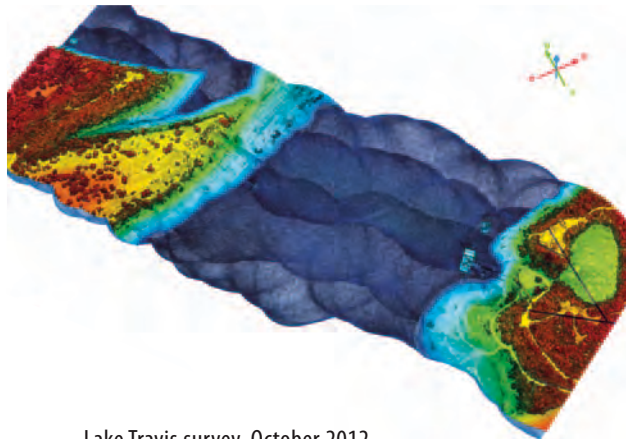
Kutalmis Saylam

As a new scientist at the Bureau who has moved here recently from Victoria, BC, Canada, I get to work with the cool lidar equipment that the Bureau has purchased from a company in Sweden. Although plenty of knowledgeable people are here at the Bureau already, I am sure my previous expertise and academic knowledge will bring a distinctive flavor to the current team.

Between 2003 and 2007, I worked for a company that manufactures lidar systems in Toronto, Canada. I was employed as a specialist, and my job required me to support and train clients from all over the world. I have traveled extensively to all inhabitable continents, providing support and training along the way. In my travels I have met many wonderful people and have explored amazing cultures while working with different kinds of remote sensing systems and supporting surveying equipment; I was hooked for life!

While undertaking my Ph.D. studies part time at the University of Calgary with the Digital Photogrammetry group, I moved to the province of British Columbia and began working as a geodetic engineer for the BC Government. I was promoted to Digital Image Services Team Leader at GeoBC and helped the agency advance in remote sensing technologies. During my tenure, GeoBC was rewarded with various satellite and lidar imaging projects—a first—and was charged with providing expertise to other public service agencies.

What makes lidar technology so special anyway? How do reflected light pulses bring back so much



Lake Travis survey, October 2012.

information? Just as in the system the Bureau has purchased, the downward-focusing sensors are installed on aircraft, and these combine many technologies to measure distances and other properties of reflected surface materials. A modern airborne lidar system installed on an aircraft will consist of a laser-beam

generator that spits out light pulses at more than 100,000 times per second. A fast-moving scanner distributes pulses to the ground, while transmitter and receiver electronics calculate the time that the beam is traveling. Onboard positional and navigational systems (GPS & IMU) determine the precise position and orientation of the sensor, and, back at the receiver, we can then determine the coordinates of each pulse that is transmitted and measured. With so many points that have already been geo-referenced, high-resolution imagery of the ground is simple to generate by using project-specific algorithms. An onboard hyperspectral sensor also provides valuable information for mining, geology, and oil industries.

The system purchased by the Bureau has distinctive features. The active sensor includes two lidar scanners having different wavelengths; 1,064 nm is used for topographic mapping and 515 to 1,030 nm is for bathymetric mapping. Both sensors may operate simultaneously, and the onboard computer distinguishes each wavelength. Additional waveform digitizers besides these two scanners will substantially increase the number of data recorded, and we will soon have terabytes of point-cloud data ready to be analyzed for all the complex projects at the Bureau!

Geologic Mapping of Landscapes in Transition

Dr. Charles (Chock) Woodruff



A geologic map—a basic product of geologic research—depicts rock units at the Earth's surface, as well as the topographic and structural arrangements among these units. As part of their definition, bedrock formations (mappable rock units) occupy specific segments of geologic time. Rock units in



any area therefore compose a stacked sequence (a geologic column) that allows geologic-map users to make inferences about the Earth's third dimension. In short, a geologic map—presented in two dimensions atop a piece of paper—allows us to imagine conditions underground. Clearly, the ability to predict the arrangement of rock packages in three dimensions is valuable to anyone seeking information on underground resources (groundwater, petroleum, or hard minerals). But the value of a geologic map goes beyond the search for traditional rock and mineral resources. Such a map also provides information on beneficial uses of the land, as well as problems that may be encountered owing to interactions among geologic substrates and landforms depicted on said map. Inferences of land-use constraints (or potentials) resulting from local materials, landforms, and geologic processes form the basis for mapping *land resources*, which was pioneered by the Bureau years ago.

During the past year, I have been mapping or revising existing geologic maps in an area of diverse bedrock, surface deposits, landforms, and hydrologic processes. This area comprises eight 7.5-minute topographic quadrangle maps encompassing shorelands of several LCRA Highland Lakes—Lake Marble Falls, Lake Lyndon B. Johnson, most of Inks Lake, upper reaches of Lake Travis,

and south margins of Lake Buchanan. The total area investigated equals about 504 mi².

This project area includes map units representing all four geologic eras: Precambrian, Paleozoic, Mesozoic, and Cenozoic. And the Colorado River and its tributaries have exhumed a

major structural uplift comprising igneous and metamorphic rocks and faulted sequences of sedimentary strata associated with margins of the now-buried Ouachita Mountain belt. Superimposed on these ancient terranes are overlapping edges of Cretaceous strata that compose dissected margins of the once-continuous Edwards Plateau. Land resources of this area include local arable land (mostly on alluvial deposits), extensive hilly rangelands, and plateau outliers. The dissected uplands would have had minimal economic value in the past, but owing to impoundments of the Highland Lakes, this land is now in great demand for homesites. In short, the area is in transition from traditional agrarian uses (mainly livestock production) and quarrying of local rock products that include limestone aggregate, sandstone for industrial uses, granite for dimension stone, and weathered granite for landscaping. Equally important today, as more people occupy this complex landscape, is the use of geologic maps to provide information on areas of possible geologic hazards and sites important to maintaining quality of surface and subsurface water resources.

My involvement with this mapping revisits work done for my doctoral research at The University of Texas at Austin during the 1970's and follow-up compilation of maps at regional scales for the Bureau (1972–1983).

- 120** Executive Administration
- 121** Administration
- 122** Grants, Accounting, and Purchasing
- 123** Core Facilities
- 124** Human Resources
- 125** Information Technology
- 126** Media Services
- 127** Log Library and Publications
- 128** External Affairs



Administrative Support

Navigating the twists and turns of a canyon and emerging at the other end unscathed and armed with useful data are the goal of many Bureau scientists, not only in the field but also figuratively in dealing with the intricacies of U.T. bureaucracy. And it is the job of the Bureau Administrative Division to light the way through the labyrinth, guiding our scientists to successful research.

Over its 100 years of existence, the Bureau has earned a tremendous international reputation that has been based on delivering top-quality research, and Bureau researchers are undeniably outstanding. However, most Bureau researchers will probably acknowledge that what is made to happen behind the scenes by our administrative staff helps them perform at their best.

The Bureau has approximately 50 administrative workers whose full-time job it is to facilitate research. These folks

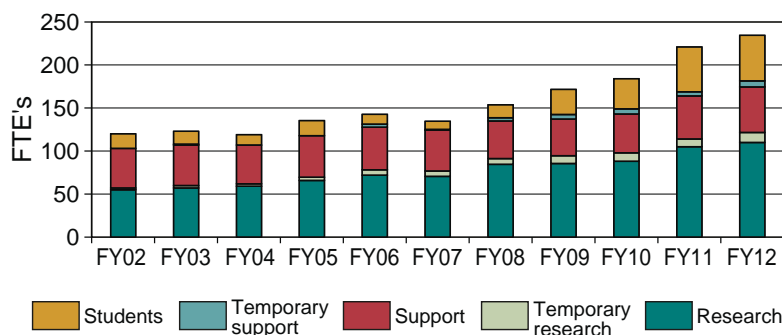
help researchers navigate through the complex U.T. bureaucratic maze and, quite simply, allow the technical staff to do what they do best—research—not administrative work. And although the number of researchers has doubled in the past decade, the support staff has not grown. That is efficiency!

In the following pages you will read about the Bureau’s outstanding administrative teams. These professionals dedicate themselves to streamlining, facilitating, and processing the activities required to keep the Bureau running and to ensure that we stay in compliance with a plethora of rules and regulations created by the State of Texas and U.T.

I am personally very proud of the work this group does and hope that you find the following sections both insightful and entertaining.

—Jay Kipper

Bureau Staff 10-Year Trend



Keeping the Wheels on the Bus

Sharon Campos, Jenny Turner, and Emily Hooks

If the Bureau were a bus and Scott Tinker were at the wheel, Eric would be the station attendant; Michael would head up the efficient, low-flow buswash; and Jay would ensure all passengers were ticketed and aboard! We three would keep the wheels turning!

Although what we each do daily differs individually, we all keep the bus moving by keeping track of calendars, meetings, travel, and, of course, email!

Sharon Campos

As Jay's assistant, I, along with my staff of six employees, keep the Bureau wheels turning. My job careens from interesting to terrifying because Jay's job is managing the Bureau's five facilities— $\frac{1}{4}$ million ft² of space in three cities!

Keeping those travel wheels turning is what my group does best. We track who is going where from booking, to approving, to ensuring rules are followed and accounts reconciled. Because the electronic travel-approval form was so successful, we created a vehicle-request form, too, and others are now using both campuswide.

Like the newly renovated lobby? We did that under Jay's direction. Build-outs take a lot of time, money, and patience. Jay finds the money to beautify the Bureau and we get it done!

Jenny Turner

As administrative assistant to Michael and Eric, I also keep the bus maintained, tires aired up and balanced, oil level checked and changed



Sharon Campos, Jenny Turner, and Emily Hooks.

when needed and ensure the transmission is working! Things move fast around here. No time for breakdowns. Getting folks to their destinations punctually is a priority. We may even speed sometimes, but you didn't hear that from me! Thank goodness we are all on the same bus!

I'm always happy to go the extra mile if I'm asked to, such

as serving as a tour guide for the Association of American State Geologists (AASG) spouses' field trips. A day of shopping in Fredericksburg, with a visit to a local winery, and another day spent at various art and history museums in Austin—all in a day's work!

Emily Hooks

Keeping the Director behind the wheel is easy—it's right where he wants to be! But when he decides to travel from Brisbane to London via Singapore in 8 days, things get a bit challenging. Or a round trip to the Middle East in 4 days? No problem! It's all about the details, after all. Imagining each step of the journey and making sure it all comes together is how I make it work. I'm grateful that it always comes together, even with last-minute adjustments!

One of the highlights of my work at the Bureau has been being a part of planning and hosting the AASG conference. As we all know, these events take work, but it always comes together beautifully and is a great opportunity to see teamwork at its best.

So get on board! The Bureau bus is ready for plenty more exciting adventures! And we'll make sure those wheels keep right on turning!

Administrative Superheroes

Sharon Campos

How does the Bureau get you from point A to point B and help you travel all over the world? How does the Bureau magically make events happen? The new lobby is absolutely beautiful! How did that happen with little (well, some) disruption? Do you need a document to be notarized, timesheets to be filled out, equipment to be purchased, a telephone to be connected, keys to the building, after-hours access—who does that? We do!

Sometimes I think that our jobs here in Admin are as difficult as herding cats. I know that every day when my reporting group walks in the door, they have no idea what the day will bring. How exciting for all of us, really—never boring, something new and different daily, and challenges every day in our quest for the Bureau to run efficiently!

My group consists of Nancy Crutcher, Pat Downs, Jennifer Edwards, Kenneth Edwards, Sammy Jacobo, and Kim LaValley. Our duties include, but are not limited to,

Frontdesk—Reception—we are at the frontline: the “Face of the Bureau.”

Travel/Event Planning—we arrange travel, including direct billing on rental cars and hotels. We also arrange special events and do the tons of paperwork required by UT to make it happen, including hotel contracts.



Nancy Crutcher, Sammy Jacobo, Sharon Campos, Pat Downs, Jennifer Edwards, Kenneth Edwards, Kim LaValley.

Inventory—we currently have \$40 million worth (2,000 pieces) of equipment/computers that must be certified every year and that are present and accounted for.

Facilities and Construction Management—need to report building problems? Yes, we are a one-stop shop for complaints about the building. Too hot? Too cold?

We report it and work to get it fixed so that you are comfortable. Want to plug in a new piece of equipment? Don't! Unless, of course, you check with us first!

Other—Phones, voicemail, after-hours access to the J. J. Pickle Research Campus.

UT Drivers, UT/Bureau Vehicles—we certify you, and we manage a 20-vehicle fleet.

WORQSPACE—a complicated system that determines the overhead of the university.

UT timesheet management.

Advanced Energy Consortium—dynamic research in nanotechnology.

Notary Public services.

The Administrative Group is a visible and involved “Face of the Bureau,” as Director Scott Tinker calls us. Our knowledge is cosmic regarding university policy and procedure, and we can deftly get you to that point B from point A!

We Help Make Things Happen

Julie Duiker

The Grants, Accounting, and Purchasing Group does much of the behind-the-scenes administrative work that begins the research process here at the Bureau, and we work hard to help our researchers devote their time to research. We actively support the mission of the Bureau by facilitating the ethical, responsible, and efficient performance of research. We help foster an environment that encourages successful research management by

Coordinating efficient and accountable management and reporting of sponsored projects, from submission to close out.

Acting as a liaison between our researchers and other departments, central administrators, and sponsors.

Supporting program management by gathering, organizing, analyzing, and reporting information to researchers, sponsors, and reporting agencies.

Providing training and information to both new and current staff.

Educating researchers and administrators about current and evolving research regulations, policies, and management practices.

Helping to locate potential funding sources.

Developing and administering systems and procedures designed to help researchers comply with Bureau and University policies, applicable voluntary standards, and regulatory and legal requirements.

We recently combined Accounting, Contracts and Grants, and Purchasing into one lean, mean,



Vicki Stratton, Gale Ashley, Kyleen Piejko, Liz Kogan, Claudia Gerardo, Julie Duiker, Amelia Bridges, Devin Krieg, Sara Clough, Sharan Happel, Jan Braboy. David Boling not pictured.

efficient, and responsive department. The integration of the units has allowed us to work together more closely, eliminate duplicative effort, and has greatly enhanced communication.

To illustrate, in 2012, we

administered 374 accounts, 121 of which were sponsored projects.

We received a total of \$36,736,048 in new funds.

We submitted 64 sponsored-project proposals.

We processed and submitted 507 purchase orders.

Meet the talented and professional staff responsible for such awesome output:

Devin Krieg	Accounts Receivable
Kyleen Piejko	Accounts Payable
Sharan Happel	Accounts Payable
Jan Braboy	Purchasing
Claudia Gerardo	Purchasing
Liz Kogan	Contracts and Grants Specialist
Amelia Bridges	Contracts and Grants Specialist
Sara Clough	Reporting Specialist
David Boling	Time Sheets and Clearing Account
Gale Ashley	Accounting
Vicki Stratton	Support

We look forward to working together in our newly formed group to find ways of better supporting researchers.

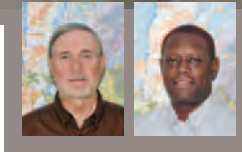
Core Values

Nathan Ivicic

The Bureau has three separate Core Research Centers (CRC's for short) that store the Bureau's massive library of geologic well samples. The facilities are located in Austin, Midland, and Houston. Combined, the three facilities contain nearly 2 million boxes of geologic material, primarily conventional core and drill cuttings, which are available to the public for viewing and, in many cases, even sampling. Employees of the CRC's are often asked to describe where they work and what they do. One common response is "Think of it as a library full of boxes of rocks instead of books." And that's precisely what the CRC's are: library facilities for geologic material. Our "core" purpose is to archive, curate, and store the physical and digital inventory of the Bureau's collection. The CRC's offer public examination rooms for layout of geologic material. We also host special events, such as core workshops.

As for the facilities themselves, the Austin CRC is located on the U.T. Pickle Research Campus, directly across the street from the main Bureau building. Built in the mid-1980's, the Austin CRC consists of a 93,000- ft² core repository and an adjacent building containing examination rooms, scientific labs, and a saw room where cores are slabbed and sampled.

The Midland CRC is located just outside the city of Midland. Its main core repository has over 50,000 ft² of dedicated core storage. The MCRC was donated



Top photo:
James Donnelly,
Joseph Smitherman,
Peter Soto-Kerans,
Brandon Williamson,
(kneeling) Daniel Valencia,
(standing, leaning on table)
Ben Grunau, Josh Lambert,
and Nathan Ivicic.
Lower photos:
(left) Randy McDonald, HRC.
(right) Darrell Haynes HRC.
(not pictured) Andy Faigle, MCRC.

to the Bureau in the mid-1990's by Shell.

On the west side of Houston, the Houston Research Center is the largest of the three facilities. It was donated to the Bureau by BP in 2002. Total facility size is 130,000 ft², including two core-storage warehouses and an

administration building containing two conference rooms and a large examination room for layout and viewing of geologic materials.

So where do all these geologic materials, primarily cores and cuttings, come from? They were donated by oil companies such as Chevron, ConocoPhillips, and Kinder Morgan. The Bureau processes and curates the donated materials, making them public domain. The collection is a magnificent resource for geologists and researchers all over the globe, and the three CRC's take great pride in maintaining

accurate physical and digital inventories, as well as safeguarding the integrity of the physical boxes and samples.

With the price of oil and gas remaining high and recent technological advances creating interest in shale plays, the CRC's have been extremely busy. We invite industry patrons, students, and researchers to take advantage of our facilities and the tremendous resource they represent, but be sure and plan ahead. A viewing request typically must be scheduled at least 2 weeks in advance. The CRC's look forward to continuing to do our part in assisting the geosciences community.

Yes, We Have a Form for That

Patty Romano

The conversation often starts with "I need to hire a...." That's when the Bureau's Human Resources team springs into action. Depending on the circumstances and type of hire, one or more members of the three-person Bureau HR team guide

the hiring supervisors from start to finish through the process of recruiting and onboarding. Because the Bureau is fortunate to hire worldwide, this task may require coordination between HR team members, as well as with representatives in central university business offices, such as Payroll or the U.T. International Office. The Bureau HR staff is highly trained and well versed in the processes for bringing our diverse staff, made up of researchers, postdoctoral fellows, support staff, and student employees, into employment with the Bureau and U.T. We are also responsible for coordinating efforts to host visiting scientists who come from all over the world to work with our researchers.

As a satellite office for the central University Human Resource Services, the Bureau HR provides coordination of recruiting and employment matters between our research unit and the wide variety of the U.T.'s central business offices, including Human Resource Services, the Jackson School Dean's office, U.T. Provost's Office, U.T. International Office, Payroll, and the Graduate Studies Office. Our mission is to offer support and assistance to new and existing Bureau employees and supervisors with issues pertaining to onboarding and ongoing employment.



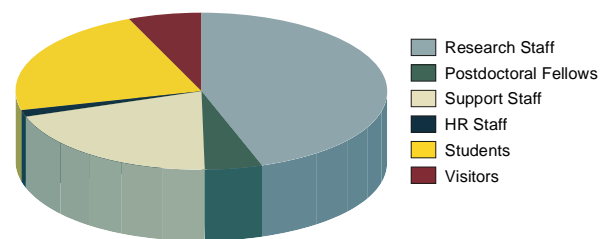
Erin Parr, Patty Romano, and Melissa Garcia.

In addition to recruiting, the Bureau HR staff is charged with keeping current with and interpreting Federal and State employment laws, as well as policies of the University. It is up to us to help ensure that our departmental human resources policies and procedures are in alignment with all

Federal, State, and University guidelines. We assist the Bureau Directorate in applying those rules within the Bureau and ensuring that all employees are current on their required compliance and ethics modules.

The Bureau HR office offers training and information on an ad hoc basis to assist supervisors with the complexities associated with management of employee performance, interview techniques, and use of the U.T.'s HR management system. We also support supervisors in developing their employee management skills—one of the most gratifying aspects of our role.

Our team genuinely enjoys helping people, and we do so as a team. The HR office is generally the first place new employees come when they have a question, and we are always happy to assist them in finding answers or pointing them toward the area that can help.



This Is IT!

Ron Russell

The staff of Information Technology Group (ITG) provides technical resources and services to Bureau scientists, support staff, and graduate students to assist their research in interpretation, 3D modeling, visualization, reservoir characterization, computer mapping, programming, database applications, and statistical and graphical analysis of data. ITG is responsible for systems and network design, as well as the purchasing, testing, installation, and training for these systems.

Bureau computing infrastructure consists of a T-1 LAN circuit connected by CISCO enterprise switches, a Dell 256 core cluster, two EMC network-attached storage (NAS) units, and a Dell NAS unit; SQL - ArcGIS specialized servers are also available. Additionally, HP Z6100s and 1055CM plotters and color printers fulfill printing needs. Major geoscience software packages are installed on the appropriate platforms to include, for



Dallas Dunlap, Joseph Su, Aaron Averett, Carlos Garza, Joseph Yeh, Reuben Reyes, and Ron Russell.

example, ABAQUS, the ArcGIS Suite, COMSOL, EDRAS (Imagine), Geolog, Gocad, Hampson Russell, the Kingdom Suite, LP360, LandMark, Matlab, Petra, Petrel, Polyworks, Surfer, and SigmaPlot.

Color-printing and plotting services are furnished by HP 1055CM and Z6100 plotters and various LaserJet printers. Additional

hardware consists of black-and-white laser printers and scanners.

ITG also provides video-conferencing and video-streaming services.

All these ITG services are made possible by a state-of-the-art computing environment composed of UNIX, Linux, Windows PC's and Macintosh computers, and support is delivered by a full-time staff of six. By the way, ITG provides these myriad programming services, along with specialized software training, while simultaneously maintaining its routine daily-support services.

Dallas Dunlap	<i>Research Scientist Associate IV</i>
Joseph Su	<i>Senior Software Developer/Analyst</i>
Aaron Averett	<i>GIS Internet Application Developer</i>
Carlos Garza	<i>Desktop Support Specialist</i>
Joseph Yeh	<i>Information Technology Specialist</i>
Reuben Reyes	<i>Senior Systems Administrator</i>
Ron Russell	<i>Senior IT Manager</i>

Bureau Media—Getting the Word Out

Cathy Brown and Lana Dieterich

If you've heard the expression *I see what you're saying*, you may understand what we do in the Bureau Media group. In fact, because education experts say that 65 percent of the population is visual learners—those who learn best when information is presented visually—*production* of visual information that is clear, concise, and correct makes sense. Our team consists of technical illustrators, editors, graphic and web designers and developers, and a photographer. And every team member gains personal and professional satisfaction from collaborating on and creating a quality product—a balance of aesthetics, precision, and attention to detail.

During project development, we ask

Does the work convey correct information in an easy-to-navigate, clear manner?

Is it appropriate to the target audience?

Does the work present the Bureau as a quality-focused organization vis-à-vis visual appeal, accuracy, and consistency?

The graphics/illustration team (John Ames, Paula Beard, Cathy Brown, Jamie Coggin, Joel Lardon, and Jana Robinson) has spent years learning to blend typography, color, illustration, and design to create work that helps tell a researcher's story or explain a concept. Typical day-to-day projects include technical illustrations, maps, presentations, ads, and scientific posters. Longer-term projects include projects published by the Bureau, such as books and Reports of Investigation. We also prepare marketing and tradeshow materials, various annual reports, and newsletters.



Paula Beard, Jana Robinson, Lana Dieterich, Cathy Brown, Jamie Coggin, Robert Newsham, Scott Rodgers, John Ames, Joel Lardon, David Stephens, and Chris Parker.

Go to any important meeting, and you'll see our photographer David Stephens quietly working to capture the spirit of the Bureau. Always in the right place at the right time, David is there with the correct lenses and lights. And as a color and photo-manipulation expert, he has honed his retouching skills to keep everyone looking good.

As Bureau editors, Lana Dieterich and Chris Parker endeavor to make Bureau scientists'

reports, papers, abstracts, and posters the best they can be. These publications are a reflection of the quality for which the Bureau has been recognized for decades, and these editors want to make all Bureau authors proud. Each one-page paper in this Annual Report was vetted by at least one editor, for example, for consistency in style, coherence, and general readability. In fact, every Bureau Best Paper Award probably began with some editorial red ink.

The Bureau homepage reaches our academic, industrial, and institutional partners, Bureau employees, and the general public. As the Bureau grows and our online presence expands, we adopt new online technologies. More than maintaining a simple internet presence, Scott Rodgers and Robert Newsham enjoy the challenge of creating an integrated information-management system using a range of specialized tools, including online publications sales, automated forms, database systems, research forums, and GIS-data distribution.

As Edward Tufte, a pioneer in information design said, "The commonality between science and art is in trying to see profoundly—to develop strategies of seeing and showing." Such is the relationship between our work and Bureau research. We enjoy using our tools and problem-solving skills to show and tell about the good work done at the Bureau!

A Curator of Texas' Natural Resources Data

Sigrid Clift

Water, petroleum, coal, uranium, and nonfuel minerals are vital resources that we use every day to maintain our way of life. Texas is fortunate to have abundant, though finite, supplies of these materials. The Resource Center here at the Bureau provides data concerning these and other Texas materials found in the Earth's crust as part of the Bureau's mission to serve as the Texas State Geological Survey. Our clients include members of the energy industry; local, State, and Federal government agencies; decision-makers; teachers and students; and landowners and other citizens. In 2012, Resource Center staff assisted these constituencies through our four main functions: (1) the Bureau Bookstore, which sold 17,000 Bureau and Gulf Coast geological societies publications; (2) the Public Information Geology office, which processed almost 800 questions and requests; (3) the Geophysical Log Facility, which scanned 80,000 Texas well logs from our 1-million-



Sigrid Clift, Dennis Campa, Daniel Ortuño, and Amanda Masterson.

log Texas collection; and (4) the Library and Map Room, which have been expanded and reorganized to better house our archives of aerial photos, contract and open-file reports, books, and donated geologic documents from 42 professional geologists and 33 companies and universities.

Each year, the Resource Center responds to an increasing number of requests from the public. As the global economy continues to grow, the demand for our finite Earth resources will likewise increase. Resource Center staff members are deeply committed to providing comprehensive assistance to our clients to ensure that they acquire the data and information that they can use to explore, develop, produce, and wisely manage the Earth's natural resources for current and future generations.

Sigrid Clift	<i>Resource Center Supervisor</i>
Dennis Campa	<i>Bookstore and Geophysical Log Facility Administrative Associate</i>
Daniel Ortuño	<i>Geophysical Log Facility Manager</i>
Amanda Masterson	<i>Bookstore Manager</i>

The Bureau's External Affairs

Mark W. Blount

The Bureau is internationally renowned for over a century of research into energy exploration and the historical documentation of those endeavors. It has helped the world to achieve a better understanding of the millions of years of Earth's evolution, its rocks, and its features. The Bureau is a key resource for the State of Texas, energy companies, policy makers, and anyone interested in our planet and our energy future. Its mission has evolved over the decades, and the Bureau is now uniquely positioned to answer questions not only related to energy exploration, but also to the economic and policy aspects of humankind's search for affordable, available, reliable, and clean sources of energy. Its extensive portfolio of environmental research is unparalleled in its investigation of the interplay of water, land, and atmospheric systems.

My job is to assure that the outside world understands what the Bureau does and to open doors for access to the new knowledge being created every day. I conduct "external affairs" for the Bureau on a number of fronts and will be promoting its image as the world's preeminent resource for information on energy and the environment. For three generations, my family and I have been involved in the energy industry. I am a Longhorn with a couple of degrees from



The University of Texas, including one in Communication, and I was a petroleum landman for over a decade. I have over 20 years' experience in philanthropic development and nonprofit management, including serving as Assistant Dean for Development in the U.T. College of Education. I also directed U.T.'s corporate relations program for 6 years, coordinating multidisciplinary relationships with UT's major company partners. I'm counting on applying that unique background to this exciting new role.

Together with the tremendous team of researchers, staff, and directors at the Bureau, I'll be disseminating information to the press and the public about the findings and the incredible expertise and resources we have on hand. Bringing new industry partners to the Bureau will be a high priority, and I'll be helping to coordinate awareness-raising events. I'll be working to solidify the Bureau's base of supporters and to develop new initiatives for educating our young people about the future of energy and the environment.

The Bureau has an extraordinary story to tell, as well as lots of new friends to make, and I'll be doing all I can to enhance its external affairs.



2012 Bureau employees.

Honors, Awards, and In Memoriam

Bureau Named One of Top Twenty Work Places

An *Austin American-Statesman* survey of 20,000 area employees has named the Bureau of Economic Geology as one of a handful of "Top Workplaces" in the city for 2012.

Dr. Scott Tinker, Director, reacted to the news: "I would like to extend my sincere congratulations to all of the talented scientists, engineers, students, staff, and management whose efforts have made UT's Bureau of Economic Geology one of the top workplaces in Austin," he said. "This honor is a tribute to each of them and their tremendous contributions to the Bureau's success." Employers making the list were nominated by their employees.

With over 200 people on its staff and a broad reputation as a world leader in energy and



environmental research, the Bureau of Economic Geology is the oldest and second-largest research unit at The University of Texas at Austin.

The *Austin American-Statesman* survey included questions concerning employers' leadership direction, training, inclusion, pay, and benefits. The Bureau was named one of Austin's Top Workplaces in the "small business" category.

Treviño Receives GCSSEPM Award



Ramón Treviño is the 2012 recipient of the GCSSEPM Distinguished Service Award. Ramón's technical and scientific contributions to

the GCCC derive from his experience in the petroleum industry, and he is a past Treasurer of GCAGS (2002) and GCSSEPM (2005–2008).

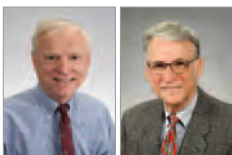
AAPG Distinguished Service Award Goes to Laura Zahm



Laura Zahm was named recipient of the AAPG Distinguished Service Award. According to the AAPG

website, this award "is presented to members who have distinguished themselves in singular and beneficial long-term service to AAPG."

AGL and STARR Authors in the Top Ten



Bob Loucks and co-author Jerry Lucia were presented an Award of Excellence as a "Top Ten" poster presentation at this year's

AAPG Convention in Long Beach, California, for their poster "Origin and Distribution of Microrhombic Calcite and Associated Micropores in the Lower Cretaceous Stuart City Tight-Gas-Carbonate Play in South Texas."

Bureau Service Awards



the Bureau and U.T. Senior Research Scientist Shirley Dutton (pictured with Director Scott Tinker) topped the list, celebrating

On May 15, the Bureau honored 18 employees at its 2012 Staff Service Awards Luncheon. The annual ceremony recognizes individuals for their service to

her 35th year of service at the Bureau. Others recognized during the ceremony included Paula Beard, Cari Breton, Melissa Garcia, Darrell Haynes, Randy McDonald, and J.-P. Nicot, 10 years of service; John Andrews, Robert Reedy, Ramon Treviño, and Hongliu Zeng, 15 years of service; Sharon Campos, Reuben Reyes, and Tom Tremblay, 20 years of service; and Lana Dieterich, Seay Nance, and Jeff Paine, 30 years of service. The event was coordinated this year by Amelia Bridges.

Poster Award Winners



of the American Association of Petroleum

Scott Hamlin and Robert Baumgardner are winners of the 2012 A.L. Cox Poster Award from the Southwest Section

Geologists for their poster on the Wolfberry Play, Midland Basin, west Texas. Covering regional stratigraphy, lithofacies, and production, the poster was judged to be "exceptional, thorough, and very understandable."

Bureau Pub Award Winners



The Bureau recognized its leading authors on April 12, at the Annual Publication Awards dinner. This year's winners of the Bureau's grand prize, the Tinker Family Publication of the Year Award, were William A. Ambrose, Tucker F. Hentz, David L. Carr, and Jeff Sprowl for their Report of Investigations: *Sequence Stratigraphy, Depositional Systems, and Hydrocarbon Play Analysis of the Pennsylvanian Cleveland Formation and Marmaton Group, Anadarko Basin, North Texas and Western Oklahoma.*



Recognition for the Landmark Publication of 2011 went to Michael R. Hudec and Martin P. A. Jackson for *The Salt Mine: A Digital Atlas of Salt Tectonics*. Also recognized for their achievements in publishing during 2011 were Andras Fall, Peter Flaig, Sergey Fomel, Qilong Fu, Ursula Hammes, Bob Hardage, John Hooker, Xavier Janson, Farzam Javadpour, Bob Loucks, Jiemin Lu, Kitty Milliken, Zahra Mohammadi, Lorena Moscardelli, Maria Nikolinakou, Chris Ogiesoba, Diana Sava, Julia Schneider, Alex Sun, Tobias Weisenberger, Jaclyn Wiggins-Camacho, Brad Wolaver, Xianli Xu, Khandaker Zahid, Hongliu Zeng, and Xiaodong Zhang.

Top 12 Prize for GCCC



Katherine Romanak, Changbing Yang, and Sue Hovorka had

their presentation at the Annual Carbon Capture, Utilization, and Sequestration Conference, April 30–May 3, selected as one of the top

12 among hundreds. Their work, “Monitoring CCS-EOR Systems Using a New Process-Based Leakage Detection Method: Assessment of Alleged CO₂ Leakage at the Kerr Farm Weyburn-Midale EOR Field, Saskatchewan,” was chosen by conference attendees on the following merits: ground-breaking, insightful, and innovative.

Awards for Romanak



The editors of *Geophysical Research Letters* selected Katherine Romanak’s paper, “Process-Based Approach to CO₂ Leakage Detection by Vadose Zone Gas Monitoring at

Geologic CO₂ Storage Sites,” as an “AGU Research Spotlight.” A general summary of the paper has been published in GRL’s online edition, and, depending on subject matter, has been

distributed to interested news media. It was also included in an *Eos* column on the back page of the newspaper. Katherine’s was also among the Top 14 Presentations for “Assessment of Alleged CO₂ Leakage at the Kerr Farm Using a Simple Process-Based Soil Gas Technique: Implications for Carbon Capture, Utilization, and Storage (CCUS) Monitoring,” which had been presented at NETL in Pittsburgh in May.

Bureau Dominates June AAPG Bulletin Cover

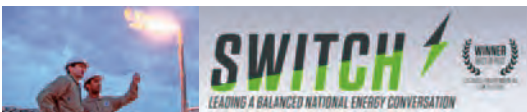


Tim Dooley and Bob Loucks shared the honor of having their photos

grace the cover of the June issue of the *AAPG Bulletin*. The large color photo is part of the paper by Tim Dooley, Mike Hudec, and Martin

Jackson, “The Structure and Evolution of Sutures in Allochthonous Salt,” which appears in this issue. The small far-left photo, the small middle photo, the small far-right photo, and the background photo are part of the paper by Bob Loucks, Rob Reed, Steve Ruppel, and Uschi Hammes, “Spectrum of Pore Types and Networks in Mudrocks and a Descriptive Classification for Matrix-Related Mudrock Pores,” which also appears in this issue of the *Bulletin*.

Switch Wins Prize



Switch, featuring Bureau Director Scott Tinker, was chosen as winner of the Colorado Environmental Film Festival’s “Best of Fest” award from among more than 50 films. Directed

by Harry Lynch, the documentary examines the world’s growing demand for energy and the choices it faces in meeting those needs. With a string of sold-out screenings across the country and critical acclaim from advocates on all sides of the energy issue, *Switch* is a departure from previous films.

Tinker Texas Monthly TIPRO Best Geoscientist



After the Texas Independent Producers & Royalty Owners

Association (TIPRO) partnered with the publishers of *Texas Monthly* and the Best Companies Group to recognize Texas oil and gas industry leaders, Bureau Director Scott Tinker was among a select group voted Best Geoscientist. In its inaugural year, the annual award is part of the group's Texas Top Producers program, and winners were featured in a special section of the August 2012 edition of *Texas Monthly*. Awardees were chosen by the vote of industry peers and professionals on the

basis of leadership, publishing and testimony, participation in technical and professional societies, mentoring and outreach, and work or studies that have led to the discovery of significant oil and gas reserves. More than 20,000 electronic ballots were distributed to identify winners. Of the 16 Best Geoscientists, *Texas Monthly* says "winners have an established reputation for their ability to map geologic strata and formations for the purpose of identifying deposits or accumulations of hydrocarbons in Texas. They also have demonstrated advanced skill in utilizing and developing technology that has led to the development of oil or gas reserves in Texas." Scott was the only academic in the group.

STARR Student Wins AAPG Prize



Student and STARR researcher Rattanaporn "Jah" Fongngern won 4th place for her poster

"Sequence Stratigraphy, Sandstone Architecture, and Depositional Systems of the Lower Miocene Succession in the Carancahua Bay Area, Texas Gulf Coast" at the American Association of Petroleum Geologists Annual Convention in Long Beach.

QCL Student Winners



Once again student researchers in the Qualitative Clastics Lab made their co-PI's, Lesli Wood and Lorena Moscardelli, proud. Trisha Alvarez is the recipient

of the ConocoPhillips SPIRIT Scholarship for \$5,000. Jessica Hudock has claimed an Ed Picou Fellowship Grant for Graduate Studies

in Earth Science of \$1,500. Vishal Maharaj has received an SEPM Research Grant of \$1,500. Damian Markez is a new Statoil Fellow, garnering \$29,000. Migdalys Salazar has won a trifecta—an Ed Picou Fellowship Grant for Graduate Studies, \$1,000; the AAPG Peter Warren Gester Memorial Grant, \$1,500; and the Jesse L. Brundrett Memorial Endowed Presidential Scholarship from the Graduate Support Committee, \$3,500. Finally, Dolores van der Kolk is the recipient of the Alexander Sisson Award, a GSA Research Grant of \$2,500.

Jackson School Awards



On December 12, during the Jackson School of Geosciences Annual Banquet and Awards Ceremony, three Bureau folks were recognized. Patty Romano, Bureau

Human Resources Manager, was awarded the JSG Staff Excellence Award. Jackson School Dean Sharon Mosher said this about Patty: "Patty Romano is someone who performs in an exemplary fashion and encourages others to aspire to superior performance. She is an important member of the Jackson School family and very deserving of this recognition. Her presence strengthens our organization."



During the same ceremony, Bob Hardage was named recipient of the Jackson School Outstanding Service and Leadership Award. Said Dean Mosher: "Bob Hardage's

career embodies a passionate quest for new applications in multicomponent seismic technologies that have impacted seismic exploration research and the seismic industry in general. Additionally, he has a long history of leadership in his service to the profession. Bob Hardage has an impressive professional background that is filled with many notable achievements that reflect his hard work, tenacity, and intelligence. He merits this recognition as a fine example of the high standards that are expected from the recipients of this award."



Finally, Sergey Fomel was presented the Jackson School Teaching Award, which was the first time the award has gone to a Bureau scientist. Dean Mosher had good things to say about

Sergey as well: "Sergey is an enthusiastic scientist who attracts young geophysicists to the field of applied data analysis. He is a superb educator in many important ways: in the classroom as a lecturer, as an advisor to M.S. and Ph.D. students and postdoctoral scientists who flock to him, and to other researchers both internally and externally. At the most recent SEG booth was inundated with prospective students, postdocs, and other colleagues wanting a chance to speak to Sergey, whom they treated like a rock star."



In Memoriam

The Bureau mourns the recent loss of John Ullo, a friend and employee at the Bureau and an exceptional researcher whose insight and counsel were key in the advancement of

BEG's Advanced Energy Consortium. Having received his Bachelor of Science degree from Rensselaer Polytechnic Institute and his Ph.D. in Theoretical Physics from Massachusetts Institute of Technology, John pursued his technical interests in mathematical modeling, computational physics, reservoir evaluation, and nanotechnology applications at Schlumberger Oilfield Services for 35 years. Serving in several R&D management positions in North America and Europe, John was Director of Research for Reservoir Evaluation at the Schlumberger-Doll Research Center from 1996 through 2001 and Vice President & General Manager of the Schlumberger Austin Technology Center from 2001 through 2004. Bureau Director Scott Tinker summarized Ullo's impact in his role in the AEC Consortium: "To John's AEC family, John was a keystone. He will be so deeply missed by all who know him. He had a fundamental impact on one of the great technical challenges of our time and one of the unique consortia of our time. I am very thankful for his vision, intelligence, expertise, and counsel."



In Memoriam

Roselle M. Girard, longtime research geologist at the Bureau of Economic Geology, died December 17, 2012, in Austin, which was also the place of her birth in 1918. She was 94. Roselle

wrote the Bureau's popular Guidebook 6, *Texas Rocks and Minerals: An Amateur's Guide*. First published in 1964, it continues to be among the Bureau's best-selling publications. She also was the author of the Bureau's early bibliography and index of Texas geology series, an essential reference for anyone conducting research on Texas geology. As part of the Bureau's cooperative program with the U.S. Bureau of Mines, Roselle collected mineral statistics for Texas; from 1960 to 1977 she was coauthor of annual reports on the mineral industry of Texas. Roselle also played a major role in developing the Bureau's annual report. She organized data regarding staff activities and accomplishments and compiled this historical document for many years. Roselle was also at the center of the Bureau's public outreach. She fielded phone calls and answered letters from school children, rockhounds, and professionals seeking information about Texas geology. Each inquiry received a well-researched and gracious reply. After 32 years of service to the Bureau, Roselle retired in 1983.

—Susie Doenges

Bureau Publications

Report of Investigations No. 276

**Anatomy of a Giant Carbonate Reservoir:
Fullerton Clear Fork (Lower Permian) Field, Permian Basin, Texas**

edited by Stephen C. Ruppel

Despite declining production rates, existing reservoirs in the United States contain large quantities of remaining oil and gas that constitute an enormous target for improved diagnosis and imaging of reservoir properties. This situation is especially true of carbonate reservoirs, in which the resource target is commonly large, but where conventional methodologies can be insufficient to resolve critical scales of reservoir heterogeneity.

This publication documents, in detail, the steps required to develop and test methodologies for improved imaging, measurement, modeling, and prediction of reservoir properties in carbonate reservoirs. The multidisciplinary study integrates geology, geophysics, petrophysics, engineering, and reservoir modeling to define reservoir architecture and the distribution of remaining oil in one of the largest carbonate reservoirs in the Permian Basin. The methods and results detailed here provide an excellent basis for improving characterization and targeting remaining resources that can be applied to all carbonate reservoirs

The extensive reservoir dataset included with this book provides a unique opportunity to examine the basic data used to conduct this study. These data may also provide important insights into the basic attributes of similar carbonate reservoirs.



Report of Investigations No. 277

Wolfberry (Wolfcampian-Leonardian) Deep-Water Depositional Systems in the Midland Basin: Stratigraphy, Lithofacies, Reservoirs, and Source Rocks

by H. Scott Hamlin and Robert W. Baumgardner

The Wolfberry play combines favorable geology with innovative completion practices to form one of the largest unconventional oil plays in the United States. Wolfberry wells produced almost 55 million barrels of oil in 2011, and potential exists for that figure to double in a few years. Abundant organic carbon, brittle calcareous mudrock, and thin permeable beds form the geologic basis for the play. The Wolfberry concept grew out of preexisting plays in low-permeability sandstones (Spraberry Formation) and detrital carbonates (Wolfcamp interval) and developed in the early 2000's through the application of modern hydraulic-fracture stimulation technology and refinement of geologic understanding of the reservoir-source-rock system. This report describes Wolfberry geology at regional and local scales and is intended to provide a context and reference for exploration and development.

The authors used wireline logs to correlate and map stratigraphic intervals and drill cores to characterize lithofacies and calibrate wireline logs for lithofacies identification and mapping beyond cored wells. On the basis of lithofacies composition, rock-body geometries, and bedding architecture, they interpreted depositional facies and elements within the sequence stratigraphic and paleogeographic framework.

Wolfberry basinal deposits are oil rich, but most lithofacies are relatively impermeable. Mudrocks are organic rich, thermally mature, and oil prone. Sandstones and carbonates are mostly thin and of poor reservoir quality. The Wolfberry reservoir-source-rock system, however, is more than 2,000 ft (610 m) thick, and by means of massive, multistage, hydraulic-fracture stimulation treatments, large volumes of marginal reservoirs are accessed and produced.



Peer-Reviewed Publications by Bureau Researchers

- Adelman, D. E., and Duncan, I. J., 2012, The limits of liability in promoting safe geologic sequestration of CO₂: *Duke Environmental Law & Policy Forum*, v. 22, no. 1, p. 1–66.
- Algeo, T. J., Henderson, C. M., Ellwood, B. B., Rowe, H. D., Elswick, E., Bates, S., Lyons, T. W., Hower, J. C., Smith, C. I., Maynard, J. B., Hays, L. E., Summons, R. E., Fulton, J., and Freeman, K. H., 2012, Evidence for a diachronous Late Permian marine crisis from the Canadian Arctic region: *Geological Society of America Bulletin*, v. 124, no. 9/10, p. 1424–1448.
- Algeo, T. J., and Rowe, H., 2012, Paleoceanographic applications of trace-metal concentration data: *Chemical Geology*, v. 324–325, p. 6–18.
- Ambrose, W. A., 2012, Chapter 1. The significance of lunar water ice and other mineral resources for rocket propellants and human settlement of the Moon, *in* Ambrose, W. A., Reilly, J. F., III, and Peters, D. C., eds., *Energy resources for human settlement in the solar system and Earth's future in space: American Association of Petroleum Geologists, Memoir 101*, p. 7–31.
- Ambrose, W. A., Breton, C., Nuñez López, V., and Gülen, G., 2012, Geologic and economic criteria for siting clean-coal facilities in the Texas Gulf Coast, USA: *Natural Resources Research*, v. 21, no. 4, p. 461–481.
- Bhandari, A. R., Powrie, W., and Harkness, R. M., 2012, A digital image-based soil deformation measurement system for triaxial tests: *Geotechnical Testing Journal*, v. 35, no. 2, p. 209–226 doi:10.1520/GTJ103821.
- Boutt, D. F., Saffer, D. M., Doan, M.-L., Lin, W., Ito, T., Kano, Y., Flemings, P. B., McNeil, L. C., Byrne, T. B., Hayman, N. W., and Moe, K. T., 2012, Scale dependence of in situ permeability measurements in the Nankai accretionary prism: the role of fractures: *Geophysical Research Letters*, v. 39, L07302, doi:10.1029/2012GL051216.
- Caldwell, T. G., McDonald, E. V., Young, M. H., and Zhu, J., 2012, Soil heterogeneity in Mojave Desert shrublands: biotic and abiotic processes: *Water Resources Research*, v. 48, W09551, doi:10.1029/2012WR011963.
- Cartwright, J. A., Jackson, M. P. A., Dooley, T., and Higgins, S., 2012, Strain partitioning in gravity-driven shortening of a thick, multilayered evaporite sequence, *in* Alsop, G. I., Archer, S. G., Hartley, A. J., Grant, N. T., and Hodgkinson, R., eds., *Salt tectonics, sediments and prospectivity: London, Geological Society, Special Publication 363*, p. 449–470.
- Carty, J. P., Connelly, J. N., Hudson, N. F. C., and Gale, J. F. W., 2012, Constraints on the timing of deformation, magmatism and metamorphism in the Dalradian of NE Scotland: *Scottish Journal of Geology*, v. 48, no. 2, p. 103–117.
- Chief, K., Young, M., and Shafer, D. S., 2012, Changes in soil structure and hydraulic properties in a wooded-shrubland ecosystem following a prescribed fire: *Soil Science Society of America Journal*, v. 76, p. 1965–1977.
- Cutright, B. L., 2012, Chapter 4. The near-Earth asteroids on the pathway to Earth's future in space, *in* Ambrose, W. A., Reilly, J. F., II, and Peters, D. C., *Energy resources for human settlement in the solar system and Earth's future in space: American Association of Petroleum Geologists, Memoir 101*, p. 75–97.
- Darabi, H., Ettehad, A., Javadpour, F., and Sepehrnoori, K., 2012, Gas flow in ultra-tight shale strata: *Journal of Fluid Mechanics*, v. 710, p. 641–658.
- Day-Stirrat, R. J., Flemings, P. B., You, Y., Aplin, A. C., and van der Pluijm, B.A., 2012, The fabric of consolidation in Gulf of Mexico mudstones: *Marine Geology*, v. 295–298, p. 77–85.
- Döll, P., Hoffmann-Dobrev, H., Portmann, F. T., Siebert, S., Eicker, A., Rodell, M., Strassberg, G., and Scanlon, B. R., 2012, Impact of water withdrawals from groundwater and surface water on continental water storage variations: *Journal of Geodynamics*, v. 59–60, p. 143–156.
- Dooley, T. P., Hudec, M. R., and Jackson, M. P. A., 2012, The structure and evolution of sutures in allochthonous salt: *AAPG Bulletin*, v. 96, no. 6, p. 1045–1070.
- Dooley, T., and Schreurs, G., 2012, Analogue modelling of intraplate strike-slip tectonics: a review and new experimental results: *Tectonophysics*, v. 574–575, p. 1–71.
- Dutton, S. P., Loucks, R. G., and Day-Stirrat, R. J., 2012, Impact of regional variation in detrital mineral composition on reservoir quality in deep to ultradeep lower Miocene sandstones, western Gulf of Mexico: *Marine and Petroleum Geology*, v. 35, p. 139–153.
- Ellis, M. A., Laubach, S. E., Eichhubl, P., Olson, J. E., and Hargrove, P., 2012, Fracture development and diagenesis of Torridon Group Applecross Formation, near An Teallach, NW Scotland: millennia of brittle deformation resilience: *Journal of the Geological Society, London*, v. 169, p. 297–310.
- Emmanuel, S., and Day-Stirrat, R. J., 2012, A framework for quantifying size dependent deformation of nano-scale pores in mudrocks: *Journal of Applied Geophysics*, v. 86, p. 29–35.
- Fall, A., Eichhubl, P., Cumella, S. P., Bodnar, R. J., Laubach, S. E., and Becker, S. P., 2012, Testing the basin-centered gas accumulation model using fluid inclusion observations: Southern Piceance Basin, Colorado: *AAPG Bulletin*, v. 96, no. 12, p. 2297–2318.
- Ferrer, O., Jackson, M. P. A., Roca, E., and Rubinat, M., 2012, Evolution of salt structures during extension and inversion of the offshore Parentis Basin (Eastern Bay of Biscay), *in* Alsop, G. I., Archer, S. G., Hartley, A. J., Grant, N. T., and Hodgkinson, R., eds., *Salt tectonics, sediments and prospectivity: London, Geological Society, Special Publication 363*, p. 361–379.
- Faroozan, R., Elsworth, D., Flemings, P. B., Bilotti, F., and Muhuri, S., 2012, The role of permeability evolution in fault zones on the structural and hydro-mechanical characteristics of shortening basins: *Marine and Petroleum Geology*, v. 29, p. 143–151.
- Foss, M. M., 2012, Chapter 3. Natural gas pricing in North America, *in* Stern, J. P., ed., *The pricing of internationally traded gas: Oxford University/Oxford Institute for Energy Studies*, p. 85–144.

- Foss, M. M., Wainberg, M. L., Gülen, G., Makaryan, R., and Volkov, D., 2012, Chapter 2.2. The impact of institutions on the economic performance of country hydrocarbon sectors, *in* Labarthe, C. M., Robles Peiro, R. H., Velázquez Roa, J. L., Enriquez Rosas, J. D., and Foreign Affairs Latinoamérica, eds., *Derecho, instituciones y desarrollo*: Mexico City, Editorial Porrúa/ITAM, p. 155–190.
- Frébourg, G., Hasler, C.-A., and Davaud, E., 2012, Uplifted marine terraces of the Akamas Peninsula (Cyprus): evidence of climatic conditions during the Late Quaternary highstands: *Sedimentology*, v. 59, p. 1409–1425.
- Frost, E. L., Budd, D. A., and Kerans, C., 2012, Syndepositional deformation in a high-relief carbonate platform and its effect on early fluid flow as revealed by dolomite patterns: *Journal of Sedimentary Research*, v. 82, no. 11, p. 913–932.
- García-Fresca, B., Lucia, F. J., Sharp, J. M., Jr., and Kerans, C., 2012, Outcrop-constrained hydrogeological simulations of brine reflux and early dolomitization of the Permian San Andres Formation: *AAPG Bulletin*, v. 96, no. 9, p. 1757–1781.
- Garland, J., Neilson, J. E., Laubach, S. E., and Whidden, K. J., 2012, Advances in carbonate exploration and reservoir analysis, *in* Garland, J., Neilson, J. E., Laubach, S. E., and Whidden, K. J., eds., *Advances in carbonate exploration and reservoir analysis*: Geological Society, London, Special Publication 370, p. 1–15.
- Graham, R., Jackson, M. P. A., Pilcher, R., and Kilsdonk, B., 2012, Allochthonous salt in the sub-Alpine fold-thrust belt of Haute Provence, France, *in* Alsop, G. I., Archer, S. G., Hartley, A. J., Grant, N. T., and Hodgkinson, R., eds., *Salt tectonics, sediments and prospectivity*: London, Geological Society, Special Publication 363, p. 595–615.
- Gulbranson, E. L., Isbell, J. L., Taylor, E. L., Ryberg, P., Taylor, T. N., and Flaig, P. P., 2012, Permian polar forests: deciduous and environmental variation: *Geobiology*, v. 10, p. 479–495.
- Hammes, U., and Frébourg, G., 2012, Haynesville and Bossier mudrocks: a facies and sequence stratigraphic investigation, East Texas and Louisiana, USA: *Marine and Petroleum Geology*, v. 31, p. 8–26.
- Harrington, R. R., and Lucia, F. J., 2012, Integration of rock fabrics and stratigraphy for petrophysical quantification of reservoir framework, *in* Ruppel, S. C., ed., *Anatomy of a giant carbonate reservoir: Fullerton Clear Fork field, Permian Basin, Texas*: AAPG Studies in Geology 63 and Bureau of Economic Geology Report of Investigations No. 276, p. 49–66.
- Hasler, C.-A., Frébourg, G., and Davaud, E., 2012, Anatomy, internal heterogeneities, and early fracture network of a Pleistocene carbonate coastal dune (Rejiche Formation, southeastern Tunisia): *Facies*, v. 58, p. 509–522.
- Hennings, P. H., Allwardt, P., Paul, P., Zahm, C., Reid, R., Alley, H., Kirschner, R., Lee, B., and Hough, E., 2012, Relationship between fractures, fault zones, stress, and reservoir productivity in the Suban gas field, Sumatra, Indonesia: *AAPG Bulletin*, v. 96, no. 4, p. 753–772.
- Hentz, T. F., Ambrose, W. A., and Carr, D. L., 2012, Reservoir systems of the Pennsylvanian lower Atoka Group (Bend Conglomerate), northern Fort Worth Basin, Texas: high-resolution facies distribution, structural controls on sedimentation, and production trends: *AAPG Bulletin*, v. 96, no. 7, p. 1301–1332.
- Hickman, S. H., Flemings, P. B., and others, 2012, Scientific basis for safely shutting in the Macondo Well after the April 20, 2010, Deepwater Horizon blowout: *Proceedings of the National Academy of Sciences of the United States of America*, v. 3, p. 1–6.
- Hooker, J. N., Gomez, L. A., Laubach, S. E., Gale, J. F. W., and Marrett, R. A., 2012, Effects of diagenesis (cement precipitation) during fracture opening on fracture aperture-size scaling in carbonate rocks, *in* Garland, J., Neilson, J. E., Laubach, S. E., and Whidden, K. J., eds., *Advances in carbonate exploration and reservoir analysis*: Geological Society, London, Special Publication 370, p. 187–206.
- Hosseini, S. A., Mathias, S. A., and Javadpour, F., 2012, Analytical model for CO₂ injection into brine aquifers containing residual CH₄: *Transport in Porous Media*, v. 94, p. 795–815.
- Hosseini, S. A., and Nicot, J. -P., 2012, Numerical modeling of a multiphase water–oil–CO₂ system using a water–CO₂ system: application to the far field of a U.S. Gulf Coast reservoir: *International Journal of Greenhouse Gas Control*, v. 10, p. 88–99.
- Hosseini, S. A., and Nicot, J. -P., 2012, Scoping analysis of brine extraction/re-injection for enhanced CO₂ storage: *Greenhouse Gas Science and Technology*, v. 2, p. 172–184.
- Huang, Y., Scanlon, B. R., Nicot, J. -P., Reedy, R. C., Dutton, A. R., Kelley, V. A., and Deeds, N. E., 2012, Sources of groundwater pumpage in a layered aquifer system in the Upper Gulf Coastal Plain, USA: *Hydrology Journal*, v. 20, p. 783–796.
- Iñigo, J. F., Laubach, S. E., and Hooker, J. N., 2012, Fracture abundance and patterns in the Subandean fold and thrust belt, Devonian Huamampampa Formation petroleum reservoirs and outcrops, Argentina and Bolivia: *Marine and Petroleum Geology*, v. 35, p. 201–218.
- Janson, X., and Madriz, D. D., 2012, Geomodelling of carbonate mounds using two-point and multipoint statistics, *in* Garland, J., Neilson, J. E., Laubach, S. E., and Whidden, K. J., eds., *Advances in carbonate exploration and reservoir analysis*: Geological Society, London, Special Publication 370, p. 229–246.
- Javadpour, F., Amrein, M., and Jeje, A., 2012, Multiscale experimental study of selective blood-cell filtration in fibrous porous media: *Transport in Porous Media*, v. 91, p. 913–926.
- Javadpour, F., Farshi, M. M., and Amrein, M., 2012, Atomic-force microscopy: a new tool for gas-shale characterization: *Journal of Canadian Petroleum Technology*, v. 51, no. 4, p. 236–243.
- Javadpour, F., and Jeje, A., 2012, Modeling filtration of platelet-rich plasma in fibrous filters: *Transport in Porous Media*, v. 91, p. 677–696.
- Ji, L., Zhang, T., Milliken, K., Qu, J., and Zhang, X., 2012, Experimental investigation of main controls to methane adsorption in clay-rich rocks: *Applied Geochemistry*, v. 27, p. 2533–2545.

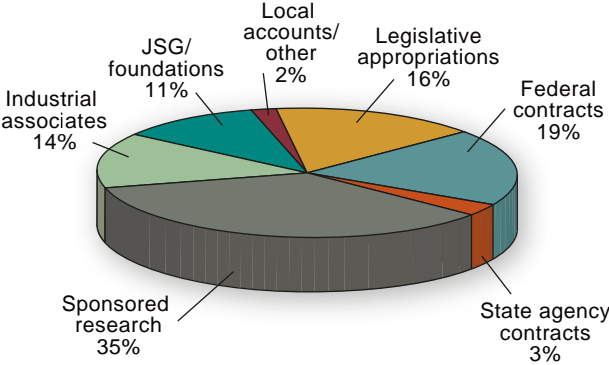
- Kane, J. A., and Jennings, J. W., Jr., 2012, Developing a wireline-log database and a basis for determining reservoir porosity, *in* Ruppel, S. C., ed., *Anatomy of a giant carbonate reservoir: Fullerton Clear Fork field, Permian Basin, Texas: AAPG Studies in Geology 63 and Bureau of Economic Geology Report of Investigations No. 276*, p. 67–76.
- Klokov, A., and Fomel, S. B., 2012, Separation and imaging of seismic diffractions using migrated dip-angle gathers: *Geophysics*, v. 77, no. 6, p. S131–S143.
- Lewis, C., Albertson, J. D., Xu, X., and Kiely, G., 2012, Spatial variability of hydraulic conductivity and bulk density along a blanket peatland hillslope: *Hydrological Processes*, v. 26, p. 1527–1537.
- Li, Y., Acharya, K., Stone, M. C., Yu, Z., Young, M. H., Shafer, D. S., Zhu, J., Gray, K., Stone, A., Fan, L., and Warwick, J. J., 2012, Spatiotemporal patterns in nutrient loads, nutrient concentrations, and algal biomass in Lake Taihu, China: *Lake and Reservoir Management*, v. 27, p. 298–309.
- Litwin, K. L., Zygielbaum, B. R., Polito, P. J., Sklar, L. S., and Collins, G. C., 2012, Influence of temperature, composition, and grain size on the tensile failure of water ice: implications for erosion on Titan: *Journal of Geophysical Research*, v. 117, E08013, doi:10.1029/2012JE004101, 14 p.
- Liu, W., Xu, X., and Kiely, G., 2012, Spatial variability of remotely sensed soil moisture in a temperate-humid grassland catchment: *Ecohydrology*, v. 5, p. 668–676.
- Liu, Y., Sun, A. Y., Nelson, K., and Hipke, W. E., 2012, Cloud computing for integrated stochastic groundwater uncertainty analysis: *International Journal of Digital Earth*, v. 5, no. 5, p. 1–25, doi:10.1080/17538947.2012.687778.
- Long, D., Scanlon, B. R., Fernando, D. N., Meng, L., and Quiring, S. M., 2012, Are temperature and precipitation extremes increasing over the U.S. High Plains? *Earth Interactions*, v. 16, p. 1–20.
- Long, D., and Singh, V. P., 2012, A modified surface energy balance algorithm for land (M-SEBAL) based on a trapezoidal framework: *Water Resources Research*, v. 48, W02528, doi:10.1029/2011WR010607.
- Long, D., and Singh, V. P., 2012, A two-source trapezoid model for evapotranspiration (TTME) from satellite imagery: *Remote Sensing of Environment*, v. 121, p. 370–388.
- Long, D., Singh, V. P., and Li, Z. L., 2012, How sensitive is SEBAL to changes in input variables, domain size and satellite sensor? *Journal of Geophysical Research*, v. 116, D21107, doi: 10.1029/2011D016542, 20 p.
- Long, D., Singh, V. P., and Scanlon, B. R., 2012, Deriving theoretical boundaries to address scale dependencies of triangle methods for evapotranspiration estimation: *Journal of Geophysical Research*, v. 117, D05113, doi:10.1029/2011JD017079.
- Loucks, R. G., Reed, R. M., Ruppel, S. C., and Hammes, U., 2012, Spectrum of pore types and networks in mudrocks and a descriptive classification for matrix-related mudrock pores: *AAPG Bulletin*, v. 96, no. 6, p. 1071–1098.
- Lu, J., Cook, P. J., Hosseini, S. A., Yang, C., Romanak, K. D., Zhang, T., Freifeld, B. M., Smyth, R. C., Zeng, H., and Hovorka, S. D., 2012, Complex fluid flow revealed by monitoring CO₂ injection in a fluvial formation: *Journal of Geophysical Research*, v. 117, B03208, doi:10.1029/2011JB008939.
- Lu, J., Kharaka, Y. K., Thordsen, J. J., Horita, J., Karamalidis, A., Griffith, C., Hakala, J. A., Ambats, G., Cole, D. R., Phelps, T. J., Manning, M. A., Cook, P. J., and Hovorka, S. D., 2012, CO₂-rock-brine interactions in Lower Tuscaloosa Formation at Cranfield CO₂ sequestration site, Mississippi, U.S.A.: *Chemical Geology*, v. 291, p. 269–277.
- Lucia, F. J., 2012, Chapter 5. The great Lower Ordovician cavern system, *in* Derby, J. R., Fritz, R. D., Longacre, S. A., Morgan, W. A., and Sternbach, C. A., eds., *The great American carbonate bank: the geology and economic resources of the Cambrian Ordovician Sauk megasequence of Laurentia: AAPG Memoir 98*, p. 83–111.
- Lucia, F. J., and Kane, J. A., 2012, Calculation of permeability and initial water saturations from wireline logs in a mature carbonate reservoir, *in* Ruppel, S. C., ed., *Anatomy of a giant carbonate reservoir: Fullerton Clear Fork field, Permian Basin, Texas: AAPG Studies in Geology 63 and Bureau of Economic Geology Report of Investigations No. 276*, p. 77–92.
- Luo, G., and Liu, M., 2012, Multi-timescale mechanical coupling between the San Jacinto fault and the San Andreas fault, southern California: *Lithosphere*, v. 4, no. 3, p. 221–229.
- Luo, G., Nikolinaou, M. A., Flemings, P. B., and Hudcok, M. R., 2012, Geomechanical modeling of stresses adjacent to salt bodies: Part 1—uncoupled models: *AAPG Bulletin*, v. 96, no. 1, p. 43–64.
- Mackey, G. N., Horton, B. K., and Milliken, K. L., 2012, Provenance of the Paleocene-Eocene Wilcox Group, western Gulf of Mexico basin: evidence for integrated drainage of the southern Laramide Rocky Mountains and Cordilleran arc: *Geological Society of America Bulletin*, v. 24, no. 5/6, p. 1007–1024.
- Mehmani, Y., Sun, T., Balhoff, M., Eichhubl, P., and Bryant, S., 2012, Multiblock pore-scale modeling and upscaling of reactive transport: application to carbon sequestration: *Transport in Porous Media*, v. 95, p. 305–326.
- Middleton, R. S., Keating, G. N., Stauffer, P. H., Jordan, A. B., Viswanathan, H. S., Kang, Q. J. J., Carey, J. W., Mulkey, M. L., Sullivan, E. J., Chu, S. P. P., Esposito, R., and Meckel, T. A., 2012, The cross-scale science of CO₂ capture and storage: from pore scale to regional scale: *Energy & Environmental Science*, v. 5, no. 6, p. 2328–7345.
- Milliken, K. L., Comer, E. E., and Marsaglia, K. M., 2012, Data report: modal sand composition at Sites C0004, C0006, C0007, and C0008, IODP Expedition 316, Nankai accretionary prism, *in* Kinoshita, M., Tobin, H., Ashi, J., Kimura, G., Lallemand, S., Sreaton, E. J., Curewitz, D., Masago, H., Moe, K. T., and the Expedition 314/315/316 Scientists: *Proceedings of the Integrated Ocean Drilling Program*, v. 314/315/316, 21 p.

- Milliken, K. L., Day-Stirrat, R. J., Papazis, P. K., and Dohse, C., 2012, Chapter 8. Carbonate lithologies of the Mississippian Barnett Shale, Fort Worth Basin, Texas, *in* Breyer, J. A., ed., *Shale reservoirs—giant resources for the 21st century*: American Association of Petroleum Geologists, Memoir 97, p. 290–321.
- Milliken, K. L., Esch, W. L., Reed, R. M., and Zhang, T., 2012, Grain assemblages and strong diagenetic overprinting in siliceous mudrocks, Barnett Shale (Mississippian), Fort Worth Basin, Texas: AAPG Bulletin, v. 96, no. 8, p. 1553–1578.
- Moscardelli, L., Dooley, T., Dunlap, D. B., Jackson, M. P. A., and Wood, L. J., 2012, Deep-water polygonal fault systems as terrestrial analogs for large-scale Martian polygonal terrains: GSA Today, v. 22, no. 8, p. 4–9. doi:10.1130/GSATG147A.1.
- Moscardelli, L., Wood, L. J., and Dunlap, D. B., 2012, Shelf-edge deltas along structurally complex margins: a case study from eastern offshore Trinidad: AAPG Bulletin, v. 96, no. 8, p. 1483–1522.
- Mukherjee, A., Scanlon, B. R., Fryar, A. E., Saha, D., Ghosh, A., Chowdhuri, S., and Mishra, R., 2012, Solute chemistry and arsenic fate in aquifers between the Himalayan foothills and Indian craton (including central Gangetic plain): influence of geology and geomorphology: *Geochimica et Cosmochimica Acta*, v. 90, p. 283–302, dx.doi.org/10.1016/j.gca.2012.05.015.
- Mukhopadhyay, S., Birkholzer, J. T., Nicot, J. -P., and Hosseini, S. A., 2012, A model comparison initiative for a CO₂ injection field test: an introduction to Sim-SEQ: *Environmental Earth Science*, v. 67, p. 601–611.
- Nicot, J. -P., 2012, Current and future water demand of the Texas oil and gas and mining sectors and potential impact on aquifers: *GCAGS Journal*, v. 1, p. 145–161.
- Nicot, J. -P., and Duncan, I. J., 2012, Common attributes of hydraulically fractured oil and gas production and CO₂ geological sequestration: *Greenhouse Gases Science and Technology*, v. 2, p. 352–368.
- Nicot, J. -P., and Scanlon, B. R., 2012, Water use for shale-gas production in Texas, U.S.: *Environmental Science and Technology*, v. 46, p. 3580–3586.
- Nikolinakou, M. A., Luo, G., Hudec, M. R., and Flemings, P. B., 2012, Geomechanical modeling of stresses adjacent to salt bodies: Part 2—poroelastoplasticity and coupled overpressures: AAPG Bulletin, v. 96, no. 1, p. 65–85.
- Ogiesoba, O. C., and Hammes, U., 2012, Seismic interpretation of mass-transport deposits within the upper Oligocene Frio Formation, south Texas Gulf Coast: AAPG Bulletin, v. 96, no. 5, p. 845–868.
- Olariu, M. I., Carvajal, R. C., Olariu, C., and Steel, R. J., 2012, Deltaic process and architectural evolution during cross-shelf transits, Maastrichtian Fox Hills Formation, Washakie Basin, Wyoming: AAPG Bulletin, v. 96, no. 10, p. 1931–1956.
- Olariu, M. I., Olariu, C., Steel, R. J., Dalrymple, R. W., and Martinius, A. W., 2012, Anatomy of a laterally migrating tidal bar in front of a delta system: Esdolomada Member, Roda Formation, Tremp-Graus Basin, Spain: *Sedimentology*, v. 59, no. 2, p. 356–378.
- Paine, J. G., Buckley, S. M., Collins, E. W., and Wilson, C. R., 2012, Assessing collapse risk in evaporite sinkhole-prone areas using microgravimetry and radar interferometry: *Journal of Environmental and Engineering Geophysics*, v. 17, no. 2, p. 75–87.
- Paine, J. G., Mathew, S., and Caudle, T., 2012, Historical shoreline change through 2007, Texas Gulf Coast: rates, contributing causes, and Holocene context: *GCAGS Journal*, v. 1, p. 13–26.
- Pomar, L., Bassant, P., Brandano, M., Ruchonnet, C., and Janson, X., 2012, Impact of carbonate producing biota on platform architecture: insights from Miocene examples of the Mediterranean region: *Earth-Science Reviews*, v. 113, p. 186–211.
- Reece, J. S., Flemings, P. B., Dugan, B., Long, H., and Germaine, J. T., 2012, Permeability-porosity relationships of shallow mudstones in the Ursa Basin, northern deepwater Gulf of Mexico: *Journal of Geophysical Research*, v. 117, B12102, doi:10.1029/2012JB009438.
- Romanak, K. D., Bennett, P. C., Yang, C., and Hovorka, S. D., 2012, Process-based approach to CO₂ leakage detection by vadose zone gas monitoring at geologic CO₂ storage sites: *Geophysical Research Letters*, v. 39, L15405, doi:10.1029/2012GL052426.
- Romanak, K. D., Smyth, R. C., Yang, C., Hovorka, S. D., Rearick, M., and Lu, J., 2012, Sensitivity of groundwater systems to CO₂: application of a site-specific analysis of carbonate monitoring parameters at the SACROC CO₂-enhanced oil field: *International Journal of Greenhouse Gas Control*, v. 5, no. 1, p. 142–152.
- Rowe, H., Hughes, N., and Robinson, K., 2012, The quantification and application of handheld energy-dispersive x-ray fluorescence (ED-XRF) in mudrock chemostratigraphy and geochemistry: *Chemical Geology*, v. 324–325, p. 122–131.
- Ruppel, S. C., 2012, Summary of reservoir characterization studies in the Fullerton Clear Fork reservoir, *in* Ruppel, S. C., ed., *Anatomy of a giant carbonate reservoir: Fullerton Clear Fork field, Permian Basin, Texas*: AAPG Studies in Geology 63 and Bureau of Economic Geology Report of Investigations No. 276, p. 1–4.
- Ruppel, S. C., and Harrington, R. R., 2012, Facies and sequence stratigraphy: critical tools for reservoir framework definition, Fullerton Clear Fork reservoir, Texas, *in* Ruppel, S. C., ed., *Anatomy of a giant carbonate reservoir: Fullerton Clear Fork field, Permian Basin, Texas*: AAPG Studies in Geology 63 and Bureau of Economic Geology Report of Investigations No. 276, p. 5–48.
- Sawyer, D. E., Flemings, P. B., Buttles, J., and Mohrig, D. C., 2012, Mudflow transport behavior and deposit morphology: role of shear stress to yield strength ratio in subaqueous experiments: *Marine Geology*, v. 307–310, p. 28–39.
- Scanlon, B. R., Faunt, C. C., Longuevergne, L., Reedy, R. C., Alley, W. M., McGuire, V. L., and McMahon, P. B., 2012, Groundwater depletion and sustainability of irrigation in the U.S. High Plains and Central Valley: *Proceedings of the National Academy of Sciences of the United States of America*, v. 109, no. 24, p. 9320–9325.

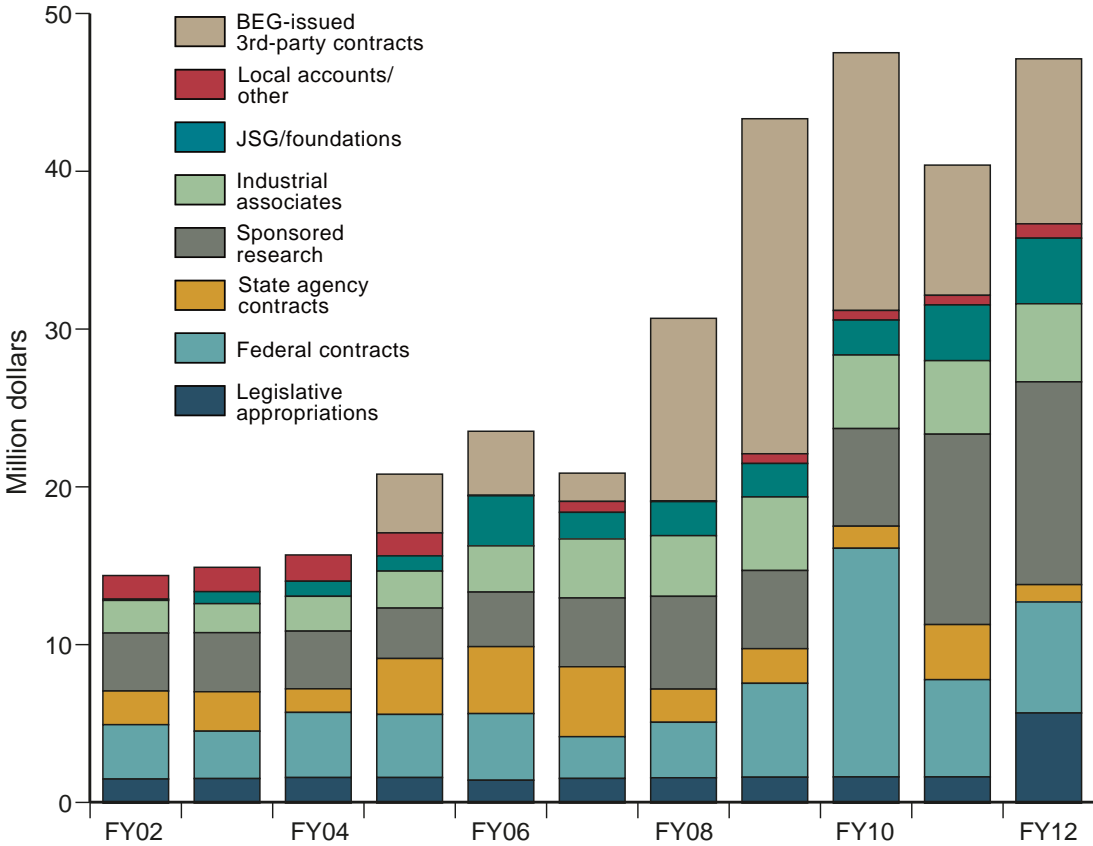
- Scanlon, B. R., Longuevergne, L., and Long, D., 2012, Ground referencing GRACE satellite estimates of groundwater storage changes in the California Central Valley, USA: *Water Resources Research*, v. 48, doi:10.1029/2011WR011312.
- Shabro, V., Torres-Verdin, C., Javadpour, F., and Sepehrnoori, K., 2012, Finite-difference approximation for fluid-flow simulation and calculation of permeability in porous media: *Transport in Porous Media*, v. 775–793.
- Stovas, A. M., and Fomel, S. B., 2012, Generalized nonelliptic moveout approximation in τ - p domain: *Geophysics*, v. 77, no. 2, p. U23–U30.
- Stovas, A. M., and Fomel, S. B., 2012, Shifted hyperbola moveout approximation revisited: *Geophysical Prospecting*, v. 60, p. 395–399.
- Sun, A. Y., Green, R., Swenson, S., and Rodell, M., 2012, Toward calibration of regional groundwater models using GRACE data: *Journal of Hydrology*, v. 422–423, p. 1–9.
- Sun, A. Y., and Nicot, J. -P., 2012, Inversion of pressure anomaly data for detecting leakage at geologic carbon sequestration sites: *Advances in Water Resources*, v. 44, p. 20–29.
- Thu, M. K., Ito, T., Lin, W., Doan, M.-L., Boutt, D., Kawamura, Y., Khong, C. K., McNeil, L., Byrne, T. B., Saffer, D. M., Araki, E., Eguchi, N., Sawada, I., Flemings, P. B., Kano, Y., Moore, C., Kinoshita, M., and Tobin, H., 2012, Operational review of the first wireline in situ stress test in scientific ocean drilling: *Scientific Drilling*, no. 13, April, p. 35–39.
- Wang, F. P., and Lucia, F. J., 2012, Reservoir modeling and simulation of the Fullerton Clear Fork reservoir, Andrews County, Texas, in Ruppel, S. C., ed., *Anatomy of a giant carbonate reservoir: Fullerton Clear Fork field, Permian Basin, Texas: AAPG Studies in Geology 63 and Bureau of Economic Geology Report of Investigations No. 276*, p. 111–143.
- Weisenberger, T., Rahn, M., van der Lelij, R., Spikings, R., and Bucher, K., 2012, Timing of low-temperature mineral formation during exhumation and cooling in the Central Alps, Switzerland: *Earth and Planetary Science Letters*, v. 327–328, p. 1–8.
- Wilson, C. R., Scanlon, B. R., Sharp, J., Longuevergne, L., and Wu, H., 2012, Field test of the superconducting gravimeter as a hydrologic sensor: *Ground Water*, v. 50, no. 3, p. 442–449.
- Wright, L., Devitt, D. A., Young, M. H., Gan, J., Vanderford, B., Snyder, S. A., McCullough, M., and Dodgen, L., 2012, Fate and transport of thirteen pharmaceutical and personal care products in a controlled and irrigated turfgrass system: *Agronomy Journal*, v. 104, p. 1244–1254.
- Xie, H., Longuevergne, L., Ringler, C., and Scanlon, B. R., 2012, Calibration and evaluation of a semi-distributed watershed model of Sub-Saharan Africa using GRACE data: *Hydrology and Earth Systems Sciences*, v. 16, p. 3083–3099.
- Xu, X., Lewis, C., Liu, W., Albertson, J. D., and Kiely, G., 2012, Analysis of single-ring infiltrometer data for soil hydraulic properties estimation: comparison of BEST and Wu methods: *Agricultural Water Management*, v. 107, p. 34–41.
- Yang, A. L., Huang, G. H., Fan, Y. R., and Zhang, X., 2012, A fuzzy simulation-based optimization approach for groundwater remediation design at contaminated aquifers: *Mathematical Problems in Engineering*, v. 2012, Article ID 986867, 13 p.
- You, Y., Flemings, P. B., and Mohrig, D. C., 2012, Dynamics of dilative slope failure: *Geology*, v. 40, no. 7, p. 663–666.
- Zahid, K., Hosseini, S. A., Nuñez López, V., and Hovorka, S. D., 2012, Characterizing CO₂ storage reservoirs and shallow overburden for above-zone monitoring in Texas Gulf Coast EOR fields: *Greenhouse Gases Science and Technology*, v. 2, p. 460–473.
- Zeidouni, M., 2012, Analytical model of leakage through fault to overlying formations: *Water Resources Research*, v. 48, W00N02, doi:10.1029/2012WR012582.
- Zeidouni, M., and Pooladi-Darvish, M., 2012, Leakage characterization through above-zone pressure monitoring: 1—inversion approach: *Journal of Petroleum Science and Engineering*, v. 98–99, p. 95–106.
- Zeidouni, M., and Pooladi-Darvish, M., 2012, Leakage characterization through above-zone pressure monitoring: 2—design considerations with application to CO₂ storage in saline aquifers: *Journal of Petroleum Science and Engineering*, v. 98–99, p. 69–82.
- Zeng, H., 2012, Construction and analysis of three-dimensional seismic porosity inversion models, in Ruppel, S. C., ed., *Anatomy of a giant carbonate reservoir: Fullerton Clear Fork field, Permian Basin, Texas: AAPG Studies in Geology 63 and Bureau of Economic Geology Report of Investigations No. 276*, p. 93–110.
- Zeng, H., Xiaomin, Z., Rukai, Z., and Qingshi, Z., 2012, Guidelines for seismic sedimentologic study in non-marine postrift basins: *Petroleum Exploration and Development*, v. 39, no. 3, p. 275–284.
- Zhang, H., Huang, G. H., Wang, D. L., Zhang, X., Li, G. C., An, C. J., Cui, Z., Liao, R. F., and Nie, X. H., 2012, An integrated multi-level watershed-reservoir modeling system for examining hydrological and biogeochemical processes in small prairie watersheds: *Water Research*, v. 46, p. 1207–1224.
- Zhang, T., Ellis, G. S., Ma, Q., Amrani, A., and Tang, Y., 2012, Kinetics of uncatalyzed thermochemical sulfate reduction by sulfur-free paraffin: *Geochimica et Cosmochimica Acta*, v. 96, p. 1–17.
- Zhang, T., Ellis, G. S., Ruppel, S. C., Milliken, K., and Yang, R., 2012, Effect of organic-matter type and thermal maturity on methane adsorption in shale-gas systems: *Organic Geochemistry*, v. 47, p. 120–131.

Bureau Finances


Bureau Bookings (net of subcontracts)



Bureau Bookings 10-Year Trend





 **THE UNIVERSITY OF TEXAS AT AUSTIN**
Bureau of Economic Geology
Jackson School of Geosciences
1 University Sta Stop E0600
Austin, Texas 78712-0398

Nonprofit Org.
U.S. POSTAGE
PAID
PERMIT 391
Austin, Texas

Address service requested

