Midyear Report 2006

BEG and Industry: The IA’s Have It!

Bureau of Economic Geology
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Director's Message

The price of gasoline has put energy squarely “above the fold” in major newspapers. Energy is complicated and therefore poorly understood by the public and decision makers. Poor understanding has led to misguided vilification of the companies that explore for and produce 85% of the world’s energy—in the form of coal, oil, and natural gas—and resulted in policy that zeroes out all Federally supported oil and gas research at a time when it is most needed. Why are Federal policy and corporate vilification so misguided?

A few background realities.

- America consumes about 100 quadrillion Btu’s (Quads) of energy every year—equivalent to about 100 trillion cubic feet of natural gas. No energy alternatives, other than nuclear, can satisfy the current scale of global demand. For reference, all wind turbines in the U.S. combined currently produce approximately 0.02 Quads of energy, or 1/5000th of total U.S. annual consumption. Although the magnitude of 100 Quads of energy is hard to fathom, China and India will soon surpass the U.S. in energy consumption.

- The global cost of the transportation infrastructure that relies on gasoline and diesel—as well as the power generation and home-heating infrastructure that relies on coal, natural gas, and fuel oil—is well into the trillions of dollars. Transitioning that infrastructure, even if energy alternatives existed that could meet the necessary scale of demand, will be tremendously expensive and take many decades.

- Energy is vital for a healthy global economy.

- A healthy global economy is required for continued investment in the environment.

- Total fossil-fuel use is decreasing only about 2% per decade.

- It will take many decades to transition to nonfossil alternatives.

The uncomfortable irony of these realities is that in order to maintain a stable economy and associated investment in the environment, the U.S. depends on a healthy fossil energy industry. The vilification of energy companies and the zeroing out of Federal oil and gas research are thus misguided. Federal and private-sector support of fossil energy research, particularly unconventional fossil energy, is required as part of a long bridge to our energy future. The U.S. needs an energy policy that is nonpartisan and strategic. Congress needs to do what is right rather than what is popular.

The following Bureau Midyear Report highlights several of the Bureau’s Industrial Associate programs that conduct basic and applied research—research which, ultimately, impacts fossil-energy production. The research teams are some of the best in the world, and I am proud of the work that they do and the impact that their research has on global energy. In my roles as Bureau Director, President of the Association of American State Geologists, Director of Texas FutureGen, candidate for President of the American Association of Petroleum Geologists, member of the National Petroleum Council, and others I will continue to dedicate myself to conveying a balanced energy message. I feel fortunate to have my vocation and avocation juxtapose in the field of energy—an area of critical importance to the Bureau, Texas, the nation, and the world.
The Bureau of Economic Geology (BEG) is celebrating an 18-year history of success in its Industrial Associates (IA) programs. The need for integrated, innovative geoscience concepts is greater now than ever before. Challenges range from exploring in ultradeep, ultraexpensive plays to optimizing enhanced oil recovery in 75-year-old fields, and from predicting flow rates in fractured tight gas reservoirs to anticipating and planning for carbon storage that will be effective for thousands of years. All of the issues selected for BEG’s Industrial Associates programs are important globally, and each program is carefully selected and staffed. Individual programs are conducted by researchers who are recognized experts in their fields and through yearly fees are supported by international industry participants.

The concept is simple: identify a research area important to industry and relevant to BEG, the Jackson School, and the University. Assemble a world-class team and help them line up financial support from multiple companies (generally $50,000 annually). This funds a small, integrated team of specialists, who benefit from the support available at BEG, such as graphics, editing, computing, accounting, human relations, and purchasing. We also benefit from interaction with other BEG projects and with sponsors’ scientists.

**BEG Industrial Associate Programs**

- Applied Geodynamics Laboratory (AGL)
- Center for Energy Economics (CEE)
- Exploration Geophysics Laboratory (EGL)
- Fracture Research and Application Consortium (FRAC)
- Gulf Coast Carbon Center (GCC)
- Laser-Assisted Analogs of Siliciclastic Reservoirs (LASR)
- Permian Basin Geological Synthesis (PBGS)
- Quantitative Clastics Laboratory (QCL)
- Reservoir Characterization Research Laboratory (RCRL)
- Sandstone Reservoir Quality in Deep Shelf Gas Play

**Membership Base** — Currently more than 60 companies, ranging from small independents to the world’s largest integrated and national oil companies, support 10 IA programs at BEG. Some companies support a single program, while others support as many as seven. The funding model ensures that the research is relevant. Sponsors provide input to research, primarily at annual review meetings.

**Technology Transfer** — To convey results to sponsors, we rely on personal contact—annual meetings, focused workshops, and field trips. We visit their offices annually to report on progress. We also maintain private Websites for sponsors containing information and software. Some IA programs offer Web-based inventories of results, such as AGL’s Salt Mine. And we strive to publish our work, after providing sponsors first crack at using the research products.

**Leveraging Industry Funding** — Each IA program leverages industry support through grants from other institutions—private, Federal, and State funding sources. Although some aspects of private research are proprietary, some aspects are shared with IA sponsors by prearrangement with the private sponsor. Our IA program research is complemented by funding from the State of Texas and by grants from the Geology Foundation of the Jackson School of Geosciences.

**Student Involvement** — Because IA programs boast longevity, well-known scientists, and multiple industry contacts, many industry-bound students specifically seek involvement with the programs. This is a direct benefit to sponsoring companies, who get the work product of enthusiastic researchers-in-training, as well as a long look at potential future employees.
The Applied Geodynamics Laboratory (AGL) is dedicated to producing innovative concepts in salt tectonics. This research comprises a mix of physical and mathematical modeling and seismic-based mapping and structural-stratigraphic analysis of some of the world’s most spectacular salt basins. AGL research focuses on a complete range of salt-tectonic styles, including extensional, contractional, and strike-slip systems.

Established in 1988, AGL is funded by a consortium of oil companies and supported by numerous software and seismic vendors. Concepts and terminology pioneered by AGL in the last 18 years have profoundly influenced salt tectonics and are now widely disseminated throughout the oil industry. AGL strives to effectively communicate these results in a variety of media. These include

The Salt Mine: An Interactive Atlas of Salt Tectonics, an HTML-based, interactive CD-ROM designed to be the most comprehensive collection of salt-tectonic images and animations ever assembled.

Major concepts developed at AGL include salt welds, salt canopies, reactive diapirs, falling diapirs, controls on shapes of passive diapirs and sheets, fault families (with the University of Colorado), extrusive origin of salt sheets (coincident with BP and Exxon), effects of multidirectional extension, squeezed diapirs, extensional turtle structures, and mock-turtle anticlines. Major research projects have been conducted in the Gulf of Mexico, Kwanza Basin, and Lower Congo Basin. Smaller projects have been undertaken in many other areas, including the Nordkapp Basin, Sverdrup Basin, offshore Mauritania, Paradox Basin, and the eastern Mediterranean. Current research is aimed at understanding salt-sheet emplacement mechanisms, subsalt pore pressures, structures associated with salt-sheet sutures, and squeezed diapirs.

AGL currently has four full-time scientists. Martin Jackson and Mike Hudec co-direct AGL and conduct seismic- and outcrop-based research. They also teach short courses and provide consulting services to AGL’s 17 member companies. Tim Dooley is in charge of AGL’s physical modeling laboratory. This lab includes three deformation rigs, automated digital photography, and a state-of-the-art, phase-based laser scanner to track the evolution of model topography through time. Our newest hire, Jozina Dirkzwager, conducts finite-element models of salt struc-
tures. Jozina is currently investigating the deformation, pore pressure, and state of stress associated with advance of allochthonous salt sheets.

AGL also works with BEG’s Lesli Wood on sequence stratigraphy and quantitative seismic geomorphology, Christopher Harrison of the Geological Survey of Canada on Arctic tectonics, Joe Cartwright of Cardiff University on eastern Mediterranean tectonics, Peter Cobbold of the University of Rennes on geomechanics, Dan Orange of AOA Geophysical on submarine geomorphology and hydrology, and Piotr Krzywiec of the Polish Geological Institute on the geology of the Polish Trough. John Andrews, Nancy Cottington, Rong Li, and Kerza Prewitt are employed full or part time to assist with drafting, image processing, and HTML authoring.

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Oblique view of thrusts in an interpreted seismic surface in deepwater Lower Congo Basin, Gabon.

Numerical model showing loading of a salt sheet by onlapping sediments.

Vertical section from the same model.
Liquefied natural gas (LNG) is increasing in importance in the North American and global energy mix. To support this growth, a number of public information and research needs must be met. The Center for Energy Economics (CEE) at the Bureau of Economic Geology is uniquely positioned to build an independent, objective, and widely accessible knowledge and education base on the role of LNG in North American energy security. In 2002, CEE established a multiyear effort that focuses on critical economics, policy, and regulatory initiatives necessary to support commercially successful, sustainable expansion of the LNG economic value chain. Our focus has been on North American import terminal capacity expansion and related considerations with respect to safety and security, North American natural gas supply-demand balances, natural gas quality and interchangeability issues, and other topics. Our work thus far has encompassed briefing papers, public education materials, and participation in public and community forums. The platform of research and outreach created through CEE has

- Enhanced knowledge available through industry, government, and research sources. In many cases, CEE has served as the starting point for public information, outreach, and research by a number of key organizations, including U.S. Department of Energy, National Association of Regulatory Utility Commissioners, Center for LNG, National Association of State Energy Officers, and many other public and private organizations.
- Provided a neutral, university-based resource for public information.
- Added new perspectives on both North American and worldwide LNG developments.
- Established a new platform for monitoring LNG developments and market structuring for this key fuel resource.

All public documents produced by CEE are available from our LNG Website at http://www.beg.utexas.edu/energyecon/lng.

Partnership for our work is made possible through contributions of a group of existing corporate sponsors. The U.S. Department of Energy/Office of Fossil Energy helps to coordinate peer reviews with other Federal agencies and commissions. Technical advisors to the consortium include ABS, CHIV, DNV, Lloyd’s Register, ICF/PTL, and SIGTTO. The government of Trinidad & Tobago and Nigeria National Petroleum Corporation participate as observers.

A key component of CEE activities is public education on natural gas and LNG. Our team developed a publicly accessible knowledge base, *Guide to LNG in North America*, a comprehensive collection of briefing papers, and other resource materials for use by an array of community and public policy leaders. It presents an overview of the LNG industry, the role of natural gas and LNG in the world, supply and demand, technologies and innovations, and data on LNG safety and security. CEE has updated all components of the online *Guide to LNG in North America* http://www.beg.utexas.edu/energyecon/lng.

**Targeted white papers and briefs**—In addition to core briefing papers and other materials that compose the online guide, short, focused research papers address high-priority questions and issues that add to the knowledge base for host communities and government officials, industry, and investment community audiences. Topics are identified and prioritized by CEE in consultation with LNG consortium sponsors, a peer advisor group, and independent experts and opinion leaders.
makers. Given the extensive input and observations, drawn largely from our primary points of contact, upcoming research reports will most likely address

- **Dynamics of natural gas pricing, LNG entry to North American markets, and natural gas supply-demand market conditions.** A widely used and quoted element of CEE's Guide to LNG in North America is our estimate of delivered (plant gate) cost for imported LNG. A priority among local decision makers and policy leaders is price impact of LNG for customers, especially small core customers on natural gas distribution networks. We think that the public domain should include accessible, transparent information on how natural gas prices are formed. A specific goal for CEE is to help customers and decision makers better understand the dynamics underlying natural gas pricing, incorporating basis and the potential impact of basis. Part of this effort includes economic impacts associated with gas quality and interchangeability. CEE will also update LNG supply-chain investments, costs, and related issues.

- **Worldwide supply for the LNG value chain.** This research coincides with CEE’s continuous research on worldwide oil and gas resource assessments and exploitation. A concern among local decision makers in all import markets (North America and worldwide) is access to foreign supplies of natural gas and energy security risks associated with those resources. We think that better information, especially clear explanations regarding structure of the global natural gas industry and roles of various participants, is critical. We anticipate that separate work products would address the global LNG supply situation more generally, with more specific products targeted to North American audiences.

- **Deeper understanding of LNG safety and security.** Much of this topic is directed to higher level audiences, especially political. Few products exist that adequately address local concerns beyond background and fundamentals presented in CEE’s LNG Safety and Security, a widely used document: important issues that require additional outreach from dispersion modeling to events and consequences. Materials that clearly lay out issues associated with potential risks and hazards and that address perceptions of risk are critical.

Imported LNG alone cannot meet U.S. natural gas supply needs, and imported LNG is only part of the long-term energy portfolio solution. CEE’s work on LNG complements a 14-year-old programmatic effort on natural gas supply and disposition in North America. Our work includes economics of frontier resources and stranded gas commercialization, as well as special projects, such as independent analysis of Alaska natural gas pipeline transportation. In addition, CEE conducts research on oil, coal, electric power, and CO₂ economics and policy with geographic coverage well beyond North America, providing a rich context for the LNG consortium effort.

The CEE team includes Michelle Michot Foss, Chief Energy Economist; Mariano Gurfinkel, Project Manager; Gürçan Gülen, Senior Energy Economist; Miranda Ferrell, Senior Energy Researcher; Ruzanna Makaryan, Senior Energy Analyst; Dimitry Volkov, Energy Analyst; and Natalie Silva, Administrative Assistant.

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**Comparison of estimated additional capacity from proposed offshore LNG terminals and LNG import forecast.**
Geophysics research at BEG concentrates on development of multicomponent seismic technology that can be used to better characterize geologic systems. We focus on design of vector seismic sources, optimization of multicomponent data-acquisition and data-processing procedures, and unified interpretation of compressional (P) and shear (S) wave images. Research is organized around the Exploration Geophysics Laboratory (EGL), an alliance of scientists from BEG and a consortium of industry sponsors. EGL, established in 1997, develops seismic vector-wavefield technology for improving reservoir characterization and prospect evaluation and applies these technologies across both onshore and offshore prospects. Investment by private sponsors has been enhanced by grants from the U.S. Department of Energy (DOE) and Minerals Management Service.

During the past several decades, the hydrocarbon exploration industry has relied on only the P-wave component of the seismic wavefield for prospect development. However, each of the other modes of the full-elastic wavefield provides additional rock and fluid information. When all modes are acquired, processed, and interpreted, seismic-based geologic information increases significantly.

To develop compelling case histories that document the value of multicomponent seismic data over conventional P-wave data is critical, and EGL is concentrating on this case-history challenge. The full elastic seismic wavefield (P-P, SH-SH, SV-SV, P-SV, SV-P) can be constructed only with 9-C data, which can be acquired only onshore and at a cost about twice that of P-wave data acquisition.

Only P-P and P-SV modes can be created using marine 4-C data because the original shear (SH) mode will not propagate through liquid media. For cost reasons, onshore operators often defer to 3-C data rather than 9-C data, thus limiting themselves to P-P and P-SV modes, such as in marine environments. EGL works with all of these data types to document advantages, as well as limitations, of multicomponent seismic data.

EGL has found that in many instances in which P-wave seismic data do not image a particular target across a prospect area, one of the other elastic wave modes (SH-SH, SV-SV, or P-SV) provides the geological information needed. Which wave mode provides the desired rock and fluid information and/or reveals the proper sequence and structure for the area varies from site to site. EGL experience and know-how can be critical to operators who need optimal seismic evaluation of complex reservoir systems.

One example of multicomponent seismic application addresses the problem of fizz-gas. Exploration and field-development drilling frequently target seismic amplitude anomalies, but for decades operators have been frustrated by the failure of poststack P-P seismic data to distinguish between reservoirs bearing gassy...
Lateral changes in petrophysical properties that control P-P and P-SV reflectivities across fluid contact boundaries. $V_p$ is P-wave velocity, $V_s$ is S-wave velocity, and $\rho$ is bulk density.

New evidence is accumulating, however, showing that when multicomponent seismic data are used to illuminate gas reservoirs, the converted-shear (P-SV) image constructed from these data can distinguish between fizz-gas and commercial reservoirs.

The leverage provided by multicomponent seismic is evident from petrophysical properties summarized in the table, which shows a reservoir interval overlying a fluid contact boundary only if the reservoir contains a commercial saturation of gas. Commercial gas should thus appear brighter in P-SV images than fizz-gas does.

EGL staff members include Milo Backus (seismic theory and applications), Mike DeAngelo (seismic modeling and interpretation), Sergey Fomel (seismic theory, imaging, and mathematics), Bob Graebner (seismic theory and applications), Paul Murray (seismic processing, theory, and applications), Randy Remington (seismic interpretation and processing), Diana Sava (rock physics, seismic theory, and applications), and Don Wagner (seismic theory and applications).

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<table>
<thead>
<tr>
<th>Reservoir</th>
<th>$\Delta V_p$</th>
<th>$\Delta \rho$</th>
<th>$\Delta V_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>No gas ($\rho_u = 100%$)</td>
<td>Modest</td>
<td>Modest</td>
<td>Modest</td>
</tr>
<tr>
<td>Fizz gas ($\rho_u = 80%$)</td>
<td>Large</td>
<td>Modest</td>
<td>Modest</td>
</tr>
<tr>
<td>Commercial gas ($\rho_u = 10%$)</td>
<td>Large</td>
<td>Large</td>
<td>Modest</td>
</tr>
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P-P and P-SV images of fizz-gas and commercial-gas reservoirs. Fizz gas produces a prominent P-P amplitude anomaly (top left) but no P-SV amplitude anomaly (top right). Commercial gas produces a prominent P-P amplitude anomaly (lower left) and a modest P-SV amplitude anomaly (lower right).
Understanding and successfully predicting, characterizing, and simulating reservoir-scale structures are the aims of the Fracture Research and Application Consortium (FRAC). A key aspect of the program is investigation of mechanical and chemical processes and interactions over a range of scales. Our goal is to improve prediction of seismic and sub-seismic heterogeneities that influence fluid flow.

The scope of this project includes measurement, interpretation, prediction, and simulation of fractures. The project will

- create and test new methods of measuring attributes of reservoir-scale fractures, particularly as fluid conduits and barriers;
- extrapolate structural attributes to reservoir scale through rigorous mathematical techniques and help build accurate and useful 3-D models for the interwell region;
- develop the capability to accurately predict reservoir-scale deformation using geomechanical, structural, diagenetic, and linked geomechanical/diagenetic models;
- improve the usefulness of seismic response as an indicator of reservoir-scale structure by providing methods of calibrating and verifying seismic fracture detection methods; and
- design new ways to incorporate geological and geophysical information into reservoir simulation and verify the accuracy of the simulation.

**Surrogate Methods.** This research aims to provide methods of acquiring site-specific fracture information at user-specified levels of completeness and yielding results without measuring elusive, difficult-to-sample, large fractures.

We are currently investigating new surrogate methods to obtain accurate, site-specific information on fracture intensity, spatial distribution, and fracture porosity preservation. We are studying automated collection of microstructural data used for (1) measuring fracture intensity and fracture orientation and applying the results to documenting variations in fracture patterns within traps and (2) calibrating seismic fracture characterization methods.

**Predictive Methods.** Direct characterization of natural fracture network attributes such as length, spacing, aperture, orientation, and intensity in most reservoirs is difficult. The problem stems mostly from the low probability of intersecting vertical fractures with vertical well bores. Even if fractures do intersect the well bore, they are rarely abundant enough to give a good representation of fracture geometry.

One promising alternative is prediction based on core-derived fracture-mechanics parameters. This process-oriented approach can provide a theoretical basis for deciding what types of fracture-attribute distributions are physically reasonable and how attributes such as length, spacing, and aperture are interrelated. The objective of the study is to improve geomechanical fracture network modeling by examining the micromechanics of the fracturing process (focused on subcritical crack growth) and by quantifying diagenetic controls on fracture-growth parameters.

Both of the foregoing research areas involve case studies in formations worldwide.

**Trap-Scale Initiative.** The current phase of the project is multidisciplinary research in analysis of fracture patterns at the trap scale. The study will
use outcrop and subsurface data from both siliciclastic and carbonate systems.

Among the issues to be addressed:

- Fracture intensity patterns on and off structure.
- Fracture style, intensity, and porosity preservation variation with structural position and burial history.
- Fracture intensity and fracture spatial arrangements at scales ranging from thin section to trap scale.

Fracture intensity and fracture patterns will be studied in the context of high-resolution data of fold geometry on outcrop analogs and horizontal core data. The aim is to use these data to guide studies of fracture seismic response.

Our research team comprises BEG staff and staff of the Departments of Petroleum & Geosystems Engineering and Geological Sciences, The University of Texas at Austin: Dr. Steve Laubach (structure and diagenesis), Dr. Jon Olson (petroleum engineering and geomechanical modeling), Dr. Randy Marrett (quantitative analysis and structural geology), Dr. Julia Gale (structural geology), Dr. Peter Eichhubl (structural diagenesis), Dr. Jon Holder (rock property testing and rock physics), Dr. Kitty Milliken (diagenesis and geochemistry), Dr. Sergey Fomel (geophysics), Dr. Rob Reed (microstructural imaging and structural geology), and Mr. John Hooker (microfracture interpretation and structural geology).

We have collaborative research arrangements as well with Drs. Rob Lander and Linda Bonnell (principals of Geocosm) to study quantitative diagenetic modeling of fracture development.

We are also proud of our graduate student staff, which has included several award-winning students, many of whom are now working in industry.

Increasing CO₂ concentration in the atmosphere is of global concern. Because the U.S. produces one-quarter of the world’s CO₂ emissions from combustion of fossil fuel, it can play a critical role in capturing CO₂ and putting it into long-term storage. BEG has formed the Gulf Coast Carbon Center (GCCC) to carry out applied research in developing strategies and protocols for long-term geologic storage of carbon in the deep subsurface of the Gulf Coast. GCCC’s vision is “to impact global levels of greenhouse gas in the atmosphere by doing science and engineering studies that will support reduction of CO₂ and methane emissions and enable development of an economically viable, multifaceted, CO₂ sequestration industry in the Gulf Coast.” GCCC is a partnership between BEG and a number of corporations, including BP, Chevron, Entergy, Kinder Morgan, Marathon, NRG, Praxair, and Schlumberger.

Industry participation in GCCC serves the mission in three ways: (1) Industry partners supply information and a “reality check” from the perspective of their industries on how carbon storage and commercialization might develop in the region. This is an interactive process, with GCCC staff members carrying out targeted research and compiling results. The partners then review these results and interact with GCCC research staff and other partners about the significance of new discoveries in understanding, resulting in development of follow-on studies and/or pilot projects. (2) Industry partners provide a sounding board for ideas from governmental agencies and Non-Governmental Organizations (NGO’s), as well as university researchers. (3) Partners provide the funding that is used to conduct research typically leveraged by additional funding from Federal, State, and industrial sources, which in turn is used to further develop GCCC’s mission.

GCCC is currently seeking to (1) assess options for reducing greenhouse-gas (GHG) emissions from point sources in the Gulf Coast; (2) foster development of a CO₂ sequestration industry; (3) facilitate communication, education, and technology transfer; and (4) address a variety of key research questions related to carbon sequestration. During 2005–2006, we have made significant advances in each area.

Options for reducing GHG emissions from point sources in the Gulf Coast include sales of CO₂ for enhanced oil recovery (EOR) and enhanced gas recovery (EGR) and storage of CO₂ in brine-bearing formations. The first activity will be sales of CO₂ for EOR, which we anticipate will act as a financial engine in developing the infrastructure for CO₂ capture and transportation. We have developed a spatial database of the volumes of CO₂ that could be captured and utilized in CO₂ EOR projects. Excluding the current area of CO₂ EOR in the Permian Basin, the potential new market for CO₂ sold for miscible EOR in areas of Texas, Louisiana, and Mississippi is 900 million metric tons. The ratio of oil recovered per unit CO₂ injected varies according to the reservoir’s properties. Estimated minimum volumes of CO₂ that could be stored within these same reservoirs are 4.4 billion metric tons, using a simple volume-for-volume replacement of oil by CO₂. This storage potential is large and would provide a good start to a storage industry on the same order of magnitude as current annual emissions for this region. Looking at the process over a 50-year period, however, we can see that these miscible reservoirs can use and then store only a small fraction of the volume emitted from point sources in the region. Other methods of storage will be increasingly important, with storage in brine formations in the forefront.

To better select reservoirs that will provide an early push to the GHG program and benefit industries that are early entrants into the GHG capture business, GCCC and UT’s Center for Petroleum and Geosystems Engineering have collaborated on developing a nonparametric model for CO₂ floods. This model, developed by Derek Woods under the supervision of Larry Lake, uses reservoir properties to estimate oil produced per pore volume of CO₂ injected. Hundreds of
simulator runs using a wide range of reservoir and fluid characteristics have been used to develop this simple and quick tool.

GCCC staff members have been studying the capacity of brine formations to store large volumes of CO$_2$. Current research focuses on issues such as how to optimize use of space beneath a specific tract of land for long-term CO$_2$ storage (an aim driven by possible liability issues) and how to predict risk of future leakage from long-term storage sites. In addition, GCCC has been working with Southeast Carbon Sequestration Partnership to look at options for storage in areas of Virginia, the Carolinas, Georgia, and Florida. GCCC is working with national collaborators to develop a standard methodology that can be used for quantifying storage capacity in diverse sedimentary basins of the U.S.

Most important, GCCC is leading three significant field activities to test conceptual and numerical models. A year of monitoring the first U.S. brine storage test—the Frio brine pilot—has been completed, and a Frio 2 follow-up study is planned for later in 2006. This study, led by GCCC, has collaborators from four national labs, the U.S. Geological Survey, and industry. A collaborative study with Kinder Morgan testing the efficacy of 30 years of CO$_2$ injection into SACROC oil field reservoirs will look for any evidence of perturbation in near-surface environments. Baseline data to be collected at a new injection in Claytonville field will allow more rigorous testing of CO$_2$ storage.

While fostering growth of a CO$_2$ storage industry, GCCC has focused on our understanding of how different components interrelate—capture, transportation, use of CO$_2$ for EOR, and storage of CO$_2$. GCCC has provided staff time and knowledge to several ventures, including a class at UT’s LBJ School, which is co-taught by Drs. David Eaton and Ian Duncan, and technical support for siting and characterizing the Texas proposal for hosting FutureGen.

A variety of research questions vital to the understanding of feasibility and potential impact of carbon sequestration are being addressed by GCCC. These questions range from purely technical concerns, such as structural and stratigraphic controls on reservoir heterogeneity that potentially impact CO$_2$ injectivity and long-term storage, to economic and infrastructure factors that may ultimately support commercialization. Key questions include:

- How can advanced reservoir characterization and innovative engineering simulations improve EOR strategies and lower capital costs?
- What are optimal strategies for injection into brines in achieving long-term storage of CO$_2$?
- What is the magnitude of any environmental impacts from historic and new CO$_2$ injections?
- What are the most effective monitoring and verification strategies for large-scale sequestration (“the gold standard”)?
- What are the optimal sites for the FutureGen Plant, given a variety of geologic and infrastructure criteria?
- What initial CO$_2$ pipeline routes best support commercialization?
- What pathways lead to commercialization of CO$_2$ sequestration?

GCCC is proud to number among its staff Sue Hovorka, Principal Investigator; Bill Ambrose, Interim Program Manager; and Mark Holtz, J. P. Nicot, Ian Duncan, Paul Knox, Joseph Yeh, Seay Nance, Becky Smith, Cari Breton, Vanessa Nunez, and Derek Wood.

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Laser-Assisted Analogs of Siliciclastic Reservoirs (LASR) is an Industrial Associate (IA) research program at the Bureau of Economic Geology that began in 2004. LASR’s mission is to (1) develop new stratigraphic concepts, (2) integrate geological and geophysical analysis into detailed outcrop characterization workflow, and (3) create teaching tools for our industrial sponsors. Our current research is focused on characterizing submarine-fan and fluvio-deltaic outcrops. We are studying several outcrops from around the world that cover a wide range of tectonic settings, physiographic positions, and architectural styles that can be used to address stratigraphic problems faced by geologists, geophysicists, and engineers in the petroleum industry.

To accomplish our mission we integrate ground lidar (light detection and ranging), GPR (ground-penetrating radar), and conventional outcrop data (for example, stratigraphic columns, correlation panels, photomosaics) to generate detailed characterizations of selected outcrops. Lidar data provide high-resolution (1- to 10-cm), three-dimensional surface models of outcrops. Stratigraphic surfaces and faults can be interpreted directly onto these data, and, as a result, the three-dimensional shape of stratal features can be accurately described. Additionally, lidar data can be used to obtain thickness and length measurements even for hard-to-access areas such as vertical cliffs. These 3D digital outcrop interpretations are used as input to generate reservoir and seismic forward models. This approach allows direct comparison between stratigraphic architectures seen in outcrop and stratal geometry imaged on seismic.

Since 2004 LASR has characterized in great detail numerous deep-water sandstone exposures: (1) Brushy Canyon Formation in West Texas (eight exposures), (2) Ross Formation in Ireland (nine exposures), (3) Capistrano Formation in California (four exposures), and (4) the Solitary Channel in Spain. Present research concentrates on the deep-water Annot Sandstone Formation in SE France and on fluvio-deltaic Ferron Sandstone in Utah, with continued work on the Ross and Capistrano Formations.

In conjunction with detailed characterization of outcrops, LASR has developed important stratigraphic concepts, fast and efficient data acquisition and processing workflows, and modern teaching tools for geoscientists.

Rinevella Point exposure, southern Loop Head peninsula, Ross Formation, Ireland. Geology of this outcrop is challenging to capture because of its location (closeness to water) and orientation (strata dipping away from exposure). (A) Point-cloud image with major stratigraphic surfaces. (B) Photographs of outcrop. (C) Correlation panel showing stratigraphic columns, bed surfaces, and facies.
Stratigraphic concepts developed by LASR over the last 2 years include (1) facies distribution, evolution, symmetry, and lateral migration of sinuous slope channels; (2) sweep and swing of sinuous slope channels; (3) secondary flow within sinuous slope channels; (4) fill and evolution of vertically stacked slope channels within channel complexes; (5) effect of sand extrusion on slope-channel stacking; (6) type and mechanism of accretionary macroforms in slope channels; (7) discrimination of key architectural elements within deep-water systems; (8) landscape evolution for confined deep-water basins; and (9) relative vertical changes in stratigraphic architecture to lateral changes in basin-margin strata.

LASR, in collaboration with BEG's RCRL (Reservoir Characterization Research Laboratory), also developed new workflows and techniques that include (1) lidar data acquisition and processing of difficult-to-access exposures, (2) construction of 3D geological and reservoir models that include lidar and conventional geological data, and (3) construction of 3D forward seismic models of outcrops. We are also integrating GPR acquisition and processing in our 2006 outcrop characterization workflow that will implement 3D geological characterization of complex 3D exposures.

Teaching tools developed by LASR make up an extensive and well-designed Website accessible by sponsors. This Website includes all LASR outcrop characterization results and stratigraphic concepts presented as interactive reports (Web modules). Many thematic reports and posters can also be downloaded, as well as self-guided, photo-draped, VRML interactive 3D models of many outcrops. Raw outcrop data (stratigraphic columns, photos, photomosaics, lidar, GPR data), as well as geological and seismic forward models (in Polyworks, GoCAD, RMS, or Petrel), can also be provided to LASR sponsors by request.

LASR and RCRL programs are acknowledged leaders in integrating lidar and conventional outcrop data for, respectively, siliciclastic and carbonate depositional systems. Lidar technology does not replace conventional outcrop analysis but, rather, supplements and improves these investigations by providing geologists with new, quantitative ways to study rocks and to digitally and remotely revisit and characterize outcrops on their computers or workstations.

The LASR team is made up of Renaud Bouroullec (stratigraphy, tectonics, and sedimentation), Mark Tomasso (stratigraphy and geologic modeling), Keumsuk Lee (stratigraphy and GPR processing), Bill Ambrose (stratigraphy), and John Andrews (3D data visualization and programming). Collaborators include David Pyles, Department of Geology and Geological Engineering, Colorado School of Mines (stratigraphy) and David Jennette, Apache Oil Corporation, Houston (stratigraphy).

The Permian Basin Geological Synthesis Project (PBGSP) is jointly funded by oil and gas industry companies and the U.S. Department of Energy. Goals of the program are to collect, synthesize, and integrate new and existing geological data on Paleozoic reservoir systems in the Permian Basin into a spatially organized and readily accessible database.

In the first year of the program, research has been directed in two areas: (1) compiling comprehensive written syntheses of major Paleozoic depositional systems in the basin and (2) conducting more focused studies on selected systems. Syntheses have now been completed for 75 percent of the reservoir systems in the basin. Three systems were chosen for detailed study during the first year: the Lower Permian Basin

Regional map of the current distribution and general lithology of rocks of Barnett age in Texas.
Devonian Thirtyone deep-water chert succession, the Upper Devonian Woodford shale succession, and the Mississippian Barnett shale succession. Available data from each of these systems have been assembled and spatially linked in an Arc/GIS database. Data assembled to date include core descriptions, core analyses, stratigraphic reservoir and regional cross sections, core photos, structure and isopach maps, and published and unpublished reports and posters.

Studies of the Barnett have focused on heretofore unknown aspects of the sedimentology and depositional history of these deep-water mudrocks (opposite page) and the nature of their fractures (see above). Early contributions of our Barnett sedimentological research include detailed documentation of the allochems, mineralogy, faunas, floras, textures, and fabrics displayed by these rocks. Fracture studies have led to important advances in our understanding of the orientation and aperture distributions of natural fractures in the Barnett, both of which have critical significance in predicting response of hydraulic fracture treatments that are necessary for effecting economic levels of production from these mudrocks.

In 2006, PBGSP is focusing on two new research problems. First, we are collecting reservoir-specific and regional data across the basin to improve our understanding of regional and local controls on the development of karst in the Lower Ordovician Ellenburger Group (see below) and the Lower Permian Clear Fork Group. Although both reservoir systems are well known to have been affected by karst, the impact of this karst on reservoir development is poorly known. Second, we are integrating 2D and 3D seismic data, as well as gravity and magnetics data, with available stratigraphic data to develop a more comprehensive understanding of the tectonic history of the basin. This more integrated analysis should provide new insights into the timing of structural events and their impact on the development of depositional systems and reservoirs.

Members of the PBGSP team include Stephen C. Ruppel (project director), Robert G. Loucks, H. Seay Nance, Wayne Wright, Julia Gale, Jeff Kane, Charles Kerans, and Edgar Guevara.


3D seismic image of zones of karst in the Ellenburger Group and associated suprastratal deformation, Benedum field, Upton County, Texas.
The Quantitative Clastics Laboratory (QCL) Industrial Associates program encompasses deep-marine, shallow-marine, and fluvial/deltaic-system morphology and characteristics in its research.

QCL has three main goals:
• To provide quality research observations, data, and products in the study of clastic systems that are timely, pertinent, and easily incorporated into our sponsors’ businesses.
• To develop predictive models of clastic-system processes, architecture, development, and response to intrinsic and extrinsic variables.
• To educate students and advance scientific understanding of the evolutionary process of clastic continental margins around the world.

Large 3D seismic and well data sets are central to the scientific goals of the project. We utilize industry-provided, 3D seismic data sets (surveys that are several thousands of square kilometers) to harvest morphometric data on various elements of deep-marine, fluvial-deltaic, and eolian depositional systems. These data provide a view of the source-to-sink evolution of continental-margin depositional systems and structure that is unattainable in outcrop study. Seismic is investigated using conventional seismic sequence framework development, quantitative seismic geomorphologic analysis, various attribute extractions, harvesting of morphologic information in ArcGIS and ErMapper, and export of these data into programs for statistical analyses of temporal and spatial distribution and relationships.

The team also works with significant outcrop data collected from around the world that provide a level of geologic detail unavailable in seismic data. Outcrop data consist of thousands of detailed facies and lithology measurements, integrated with more than 100 km of detailed architectural drawings of photopanoramic images and significant subsurface logs integrated with outcrops, as well as facies porosity, permeability, and velocity measurements. Subseismic morphometrics of reservoir bodies are also being harvested from these studies.

All information collected and interpreted by the team is conditioned and included in the SAnD Box—an html-based sedimentary analogs database. These seismic- and outcrop-derived research results form the basis for probabilistic models of reservoir occurrence, character, and evolution. 3D visualizations of these research results are conveyed to members, as are statistical data sets and vrml-based training modules, and are combined with results from published works and previous studies.

Outcrops currently under study include Cretaceous units of the western U.S., Tertiary clastics of onshore Trinidad, and coarse-grained turbidites of the Eocene-age Scotland Formation of Barbados. Areas currently under 3D seismic study include Sunda Shelf, West Natuna Basin, Indonesia; eastern-shelf, slope, and
The need for well-trained, aggressive new staff is evident in the industry today. QCL trains more students than any Industrial Associates research group in the Jackson School of Geosciences. Our students are well versed in the concepts of the scientific process and the tools needed to get research done. They learn how to work on a research team toward a common goal, and they exhibit personal achievement by winning awards and publishing in peer-reviewed journals.

The high uncertainty and cost of exploring in deep-marine settings around the world demand a dense, quantitative, architectural database with which to make deterministic and probabilistic decisions. QCL is providing these data. Ongoing development and harvesting of shallow-marine and terrestrial reservoir systems demand increasingly comprehensive understanding of how to interpret complex reservoir architecture and how to better utilize 3D seismic and dense-well databases to improve field design and increase production. We are focused on developing new approaches via quantitative seismic geomorphology to improve geoscience understanding of the nature of fluvial-deltaic systems in the subsurface rock record.

QCL is committed to pushing the envelope in collecting quantitative data and developing new concepts to improve the value of assets, as well as disseminating information and training geoscientists to increase their positive impact.

QCL staff members include Lesli J. Wood, Principal Investigator (seismic geomorphology and subsurface and outcrop studies); John Andrews, Programmer and Visualization Specialist (GIS and ERMAPPER); Paula Beard, Webmaster (SAnDBox design); Dallas Dunlap (visualization and seismic interpreter); Stacey Bilich (lab technician and field geologist); a Postdoctoral Research Associate (statistical analysis and paleoclimate applications); Graduate Research Assistants Nysha Chaderton, Sean Sullivan, Lorena Moscardelli, Carla Sanchez, Julie Maher, Ryan Ewing, Jed Flint, and Terence Campbell; and Drs. Ron Steel, David Mohrig, and Paul Mann, Collaborating Researchers.


deep-marine regions of offshore Trinidad; U.S. Gulf of Mexico proximal shelf; Kuparuk field area, Alaska North Slope; and Western Offshore, Sufi Her area, Morocco. The GOM Marco Polo 3D and GOM Mad Dog 3D Surveys are under discussion for possible inclusion in the program as well.
Reservoir Characterization Research Laboratory

The mission of the Reservoir Characterization Research Laboratory (RCRL) is to use outcrop and subsurface geologic and petrophysical data from carbonate reservoirs as the basis for developing new and integrated methodologies that will help us better understand and describe the 3-D reservoir environment and accurately predict reservoir performance. Current membership includes Anadarko, Aramco, BP, Chevron, ConocoPhillips, ENI, ExxonMobil, Great Western Drilling, Kinder Morgan, Marathon, Norsk Hydro, Oxy Permian, Pioneer, PDO, Shell, and Statoil. Our industrial sponsors receive research results at annual review meetings, on CD’s, in preprints of publications, during short courses on geologic and engineering aspects of our research, and at a mentoring program in which we work hands-on with industry staff using their data sets. In addition, our results are posted in a password-protected part of our Website—http://www.beg.utexas.edu/indassoc/rcrl/index.htm.

Our sponsor enrollment, supplemented by grants, supports five professional staff members and varying numbers of graduate student research assistants, as well as strong computer, editing, and graphics services.

In 1988, the Bureau of Economic Geology initiated RCRL as an industry-sponsored research project aimed at maximizing hydrocarbon recovery for existing carbonate reservoirs. The focus of this project was on improving methods of constructing reservoir-flow models by integrating geological and engineering data from both the outcrop and subsurface.

Initial studies focused on San Andres, Grayburg, and Clear Fork Permian outcrops and reservoirs in the Permian Basin, West Texas. These studies resulted in a robust approach to constructing geological models and flow models of stratigraphically dominated carbonate reservoirs. The key to this approach is integrating sequence stratigraphy, rock-fabric petrophysics, and spatial geostatistics. Later projects focused on Lower Cretaceous reservoirs of the Middle East (studies concentrated on the Shuaiba Formation in Qatar and Oman) using extensive Cretaceous outcrops located in Southwest Texas. Results of these studies supported a basic approach to building reservoir models developed in the Permian, although defining high-frequency cycles was more difficult because of the lack of a strong eustatic signal. We have also studied rock-fabric/petrophysical relationships and sequence stratigraphic relationships in the Jurassic Ghawar reservoir, Saudi Arabia. As a result of these studies, RCRL has garnered extensive experience in carbonate reservoir modeling, which is available to sponsors.
RCRL continues to conduct studies of subsurface reservoirs and outcrop reservoir analogs. However, the focus has moved from matrix petrophysical properties to nonmatrix petrophysics, including karst porosity, collapse brecciation, fracturing, and massive dissolution. Nonmatrix pore space is typically larger than cores and requires large rock volumes to study. The RCRL approach is to use CT scans of outcrop samples to image large pore space for study, as well as flow experiments from closely spaced shallow wells and detailed studies of vuggy outcrops at the 10-ft scale.

New areas of investigation include (1) using ground-based laser imaging in the study of outcrops, (2) building seismic outcrop models, and (3) investigating the geometry and origin of carbonate slope deposits. Ground-based laser imaging allows us to construct true 3D images of outcrop models and to collect accurate facies dimensions. Outcrop seismic models provide a basis for improving methods of interpreting subsurface seismic volumes. Most of our past stratigraphic work has been conducted on ramp and platform tops, and slope studies are aimed at achieving an understanding of geometries, origins, and petrophysics of carbonate slope deposits. The justification for all these studies is to improve the ability of the petroleum industry to construct realistic reservoir models so that it can make better predictions of reservoir performance.

RCRL principal staff members include Dr. Charles Kerans, Geology Professor (Principal Investigator); Mr. F. Jerry Lucia, Geological Engineer (Principal Investigator); Dr. James W. Jennings, Jr., Reservoir Engineer (Principal Investigator); Dr. Xavier Janson, Geologist; and Mr. Jerome A. Bellian, Geologist.

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The deep shelf gas play in the Gulf of Mexico (GOM) is focusing exploration attention below 15,000 ft in the shallow waters of the offshore Texas State leases. Ultradeep wells targeting large structures below the present-day Texas shelf are being drilled to depths of 20,000 ft to more than 30,000 ft for sandstones deposited in lowstand systems tracts. At these depths the greatest unknown and most critical risk factor is reservoir quality. Our ability to predict reservoir quality (porosity and permeability) and physical characteristics of ultradeep reservoir rocks has lagged behind our understanding of other parts of the petroleum system, such as depositional facies, traps, and petroleum migration.

BEG’s Stratigraphic Architecture and Sandstone Reservoir Quality in Deep Shelf Gas Plays of Texas State Waters project (Deep Shelf Gas) is supported by a consortium of companies. Major goals are to decrease exploration risk by (1) mapping general stratigraphic architecture and areas of deep to ultradeep depocenters from 3-D seismic data and (2) understanding the uncertainty involved in preserving porosity and permeability at depth. The project is focused on Texas State Waters and adjacent areas of onshore Texas and the Federal Outer Continental Shelf (OCS). This multidisciplinary study includes (1) mapping of deep stratigraphic architecture from seismic data, (2) isochron mapping of deep sedimentary packages, (3) seismic facies analysis of these packages, (4) petrographic analysis of rock samples, (5) statistical analysis of porosity/permeability relationships, and (6) wireline-log analysis of complete vertical data coverage in deeply drilled areas.

Data for this project include hundreds of thin-section analyses from cores as deep as 23,522 ft, several thousand porosity and permeability analyses, digitized wireline-log suites for petrophysical analysis, and a 3-D seismic data volume (supplied by Seismic Exchange, Inc.) of Texas State Waters that covers $15 \times 220$ mi ($3,300$ mi$^2$ of data). The quality of the seismic data allows analysis of the complete Tertiary section. It appears that usable data are available down to 8-s two-way traveltime.

Seismic analysis provides a clear picture of structural and stratigraphic architecture of the State Waters area. Both extensional and compressional structural features are being mapped and integrated with the sequence stratigraphic history of the basin. Sand depocenters are being identified, and the products...
identify fairways of potential, deeply buried sandstones that may be reservoirs.

Previous petrographic studies of the shallower Tertiary sandstone section have shown that significant regional variation in reservoir quality is controlled by differences in detrital mineralogy, grain size and texture, depositional environment, burial history, and geothermal gradient. The Deep Shelf Gas project builds on this earlier work and analyzes regional and depth variations in reservoir quality of deep Tertiary sandstones (>15,000 ft) from the onshore Texas Gulf Coast and the continental shelf. A major goal was to place sandstones that were studied into a structural and sequence-stratigraphic framework so that we could learn how reservoir quality is affected by changes in structural styles and depositional setting.

During the first year of this 2-year study, our focus was on the north half of the Texas coast. This year the project is investigating the south half of the Texas coast. Additional industrial sponsors are invited to join the project.

The Deep Shelf Gas team comprises Shirley P. Dutton, Robert G. Loucks, Angela McDonnell, Fred Wang, Jeff Kane, Caroline L. Breton, Romulo Briceno, L. Frank Brown, Younis Altobi, Tiffany Hedayati, Nia Nikmanesh, and Blake Walker.

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General sequence stratigraphic architecture for the Texas Gulf Coast area. The deep shelf gas play of lowstand deposits is outlined by red box.

Thin-section photomicrograph of a Frio sandstone showing secondary pore in dissolved feldspar.

Oligocene Frio and Vicksburg sandstone composition along the Texas Gulf Coast.