GRI-96/0136

Improved Resource Characterization Technology

FINAL REPORT

(November 1982–March 1996)

Prepared by

Stephen E. Laubach

Bureau of Economic Geology
Noel Tyler, Director
The University of Texas at Austin
Austin, Texas 78713-8924

for

GAS RESEARCH INSTITUTE
Contract No. 5082-211-0708
John Hansen, GRI Project Manager

June 1996

QAe7879

DISCLAIMER

50272-101

REPORT DOCUMENTATION PAGE	1. REPORT NO. GRI-96/0136	2.	3. Recipient's Accession No.
4. Title and Subtitle Improved Resource Characterization Technology: Final Report			5. Report Date March 1996
			6.
7. Author(s) S. E. Laubach			8. Performing Organization Rept. No.
9. Performing Organization Name and Address Bureau of Economic Geology The University of Texas at Austin University Station, Box X Austin, TX 78713-8924			10. Project/Task/Work Unit No.
			11. Contract(C) or Grant(G) No. (C) 5082-211-0708 (G)
12. Sponsoring Organization Name and Address Gas Research Institute 8600 West Bryn Mawr Avenue Chicago, IL 60631		Project Manager: John Hansen	13. Type of Report & Period Covered Final Report 11/1/82–3/31/96
			14.
15. Supplementary Notes			

16. Abstract (Limit: 200 words)

To enhance the application of research results by industry, this report provides a guide to results of research carried out by the Bureau of Economic Geology in the Geological Analysis of Primary and Secondary Tight Gas Sands Objectives Project as part of the Gas Research Institute (GRI) Tight Gas Sands Research Program in the period 1982–1996. The Gas Research Institute (GRI) has supported geological investigations designed to develop the knowledge necessary to produce gas from low-permeability sandstones efficiently. As part of that program, the Bureau of Economic Geology has conducted in-depth research on most of the important low-permeability sandstones in the lower 48. Another objective was to develop advanced technologies, verified in the field, which are necessary for continued cost-competitive production from low-permeability reservoirs. An extensive body of knowledge about many aspects of the geology and engineering attributes of low-permeability sandstones has been developed. We review some of the key findings of the geologic studies published in GRI topical reports and Bureau of Economic Geology monographs, refereed journal papers, contributions to other GRI reports, and papers and abstracts in meeting transaction volumes.

17. Document Analysis a. Descriptors

tight gas sandstones, reservoir development, stratigraphy, diagenesis, stress, natural fractures

b. Identifiers/Open-Ended Terms

influence of geology on reservoir properties, national survey of gas resources in low-permeability sandstones

c. COSATI Field/Group

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages
Release unlimited	Unclassified	32
	20. Security Class (This Page)	22. Price
	Unclassified	

(See ANSI–Z39.18) *See Instructions on Reverse* OPTIONAL FORM 272 (4-77) (Formerly NTIS–35) Department of Commerce

RESEARCH SUMMARY

Title	Improved Resource Characterization Technology: Final Report
Contractor	Bureau of Economic Geology, The University of Texas at Austin, GRI Contract No. 5082-211-0708, "Geologic Analysis of Primary and Secondary Tight Gas Sands Objectives."
Principal Investigator	S. E. Laubach
Report Period	November 1982–March 1996 Topical Report
Objectives	To enhance the application of research results by industry, this report provides a guide to results of research carried out by the Bureau of Economic Geology in the Geological Analysis of Primary and Secondary Tight Gas Sands Objectives Project as part of the Gas Research Institute (GRI) Tight Gas Sands Research Program in the period 1982–1996.
Technical Perspective	The Gas Research Institute (GRI) has supported geological investigations designed to develop the knowledge necessary to produce gas from low-permeability sandstones efficiently. As part of that program, the Bureau of Economic Geology has conducted in-depth research on most of the important low-permeability sandstones in the lower 48. Another objective was to develop advanced technologies, verified in the field, which are necessary for continued cost-competitive production from low-permeability reservoirs.
Results	An extensive body of knowledge about many aspects of the geology and engineering attributes of low-permeability sandstones has been developed.
Technical Approach	We review some of the key findings of the geologic studies published in GRI topical reports and Bureau of Economic Geology monographs, refereed journal papers, contributions to other GRI reports, and papers and abstracts in meeting transaction volumes.
Project Implications	The importance of new geological analysis methods and detailed resource characterizations in low-permeability gas sandstone formations has been realized for many years by GRI. Through GRI-funded research, the understanding of the geologic processes affecting the source, distribution, and recovery of gas from these reservoirs has been greatly enhanced.

CONTENTS

Objective of This Report

This report provides a final report on studies completed at the Bureau of Economic Geology under the Gas Research Institute contract Geological Analysis of Primary and Secondary Tight Gas Sands Objectives during the period 1982 through 1996. We review some of the key findings of the geologic studies published in 29 GRI topical reports and 102 Bureau of Economic Geology monographs, refereed journal papers, contributions to other GRI reports, and papers and abstracts in meeting transaction volumes. This report is intended to be a directory to this literature and to enhance the application of research results by industry. Research results cover a broad range of regions, formations, and geologic and engineering topics, and have been published in both geologic and engineering journals, as well as in GRI topical reports.

The first section, *Evolution of Geologic Investigations,* traces the history of the project. In the following section, *Research Approaches*, we summarize some of the main elements of reservoir characterization and geological analysis that are incorporated into many of the reports developed in this project. This summary section could not be comprehensive without repeating the reports themselves, so it should be regarded as a broad overview of methods rather than a complete listing of topics. In the section *Review of Technology Transfer Success* two measures of the dissemination and influence of this research on industry and the geological and engineering community at large are described. The final section, *An Annotated Summary of Project Publications*, is a list of the major topical reports and monographs, with brief summaries of their contents, and a list of other publications that stem directly from the project.

Evolution of Geologic Investigations

Since 1982 the Gas Research Institute (GRI) Tight Gas Sands Program has supported geological investigations designed to develop the knowledge necessary to produce gas from low-permeability sandstones efficiently. As part of that program, the Bureau of Economic Geology has conducted in-depth research on low-permeability sandstone in the Lower Cretaceous Travis Peak and Jurassic Cotton Valley Formations of East Texas, the Upper Cretaceous Corcoran and Cozzette sandstones of Colorado, the Upper Cretaceous Frontier Formation of Wyoming, the Pennsylvanian Sonora and Ozona Canyon and Davis Sandstones of Texas, the Pennsylvanian Cleveland Formation of Texas and Oklahoma, and the Paleocene Wilcox Lobo Formation of South Texas, as well as conducting topical studies of other low-permeability sandstones and compiling two major national summaries of low-permeability sandstone reservoir attributes. A goal of the research was to develop advanced methods for analysis and improved understanding of the formations studied in depth and to apply methods and results to other formations to enable greater recovery of gas in place in low-permeability reservoirs.

Geologic analysis of low-permeability sandstones by the Bureau of Economic Geology began in 1982 with a national assessment of low-permeability reservoirs suitable for an extensive research program. The next phase of study involved detailed evaluation of six tight gas sandstones and the selection of two of these units for comprehensive geologic, engineering, and petrophysical assessment: the Lower Cretaceous Travis Peak Formation in East Texas and northern Louisiana and the Upper Cretaceous Corcoran and Cozzette Sandstone Members of the Price River Formation (Mesaverde Group) in the Piceance Basin of Colorado. Because of limited development of the Corcoran and Cozzette at that time, detailed study of the genetic stratigraphy focused on three contiguous fields that contained most of the Corcoran–Cozzette production. In contrast, evaluation of the Travis Peak emphasized the establishment of a basinwide stratigraphic and structural framework across East Texas and North Louisiana.

In the subsequent phase of study, which required operator activity and cooperation, core and production data were collected extensively from cooperative wells drilled in the Travis Peak Formation. A total of 1,280 ft of Travis Peak core was drilled by GRI in seven cooperative wells, from which operating companies allowed GRI contractors to collect data, and an additional 1,440 ft of existing core was loaned or donated by operators. Research on the Corcoran and Cozzette Sandstones received lower priority during this phase of the project because operator activity in the Piceance Basin declined as a result of market conditions. However, one cooperative well was drilled through the Corcoran–Cozzette Sandstones to the underlying Sego Sandstone, and a total of 270 ft of core was recovered.

The first phase of geologic, engineering, and petrophysical assessment of the Travis Peak lasted from 1983 through 1986. Information gained from the cooperative wells, combined with detailed characterization of two regionally productive trends, or fairways, within the Travis Peak study area, led to drilling by GRI of three Staged Field Experiment (SFE) wells in the second phase of the Travis Peak study. The SFE wells were drilled and completed by GRI specifically for research on low-permeability gas reservoirs. SFE No. 1 was drilled in Waskom field, Harrison County, Texas, in August 1986, and SFE No. 2 was drilled in North Appleby field in September 1987. Research on these two wells focused on productive sandstones near the top and base of the Travis Peak Formation. Research on SFE No. 3, drilled in September 1988 in Waskom field, focused on the low-permeability Taylor Sandstone in the lower Cotton Valley Formation. The purpose of drilling this well was to test the transfer of technologies, techniques, and models developed during study of the Travis Peak Formation to another formation, the Cotton Valley, that has a similar stratigraphic and tectonic setting. A total of 1,050 ft of core was taken from the three SFE wells.

The next phase of the project was to extend and apply, in a new area, techniques for the geological, geophysical, and engineering characterization of low-permeability reservoirs that were developed during work on SFE wells 1 through 3. This work would eventually involve drilling several cooperative wells and the SFE No. 4 well in a formation and basin having a set of geologic and engineering attributes substantially different from the Lower Cretaceous formations of East Texas. Part of the motivation for selecting another basin was that geologic variability has a vital effect on the success of engineering assessments and operations, and that in order to be robust, technical engineering solutions require testing in contrasting geologic settings. The process of selecting a site for SFE No. 4 began with an appraisal of 183 low-permeability formations in all major low-permeability gas producing areas across the country. From a group of four candidate formations that were reviewed in detail by the Bureau, the Upper Cretaceous Frontier Formation in the Green River Basin of southwestern Wyoming was selected as the site of SFE No. 4 on the basis of the scientific challenges and lessons that it provided, high incremental resource potential, and strong operator activity.

Information gained from three successful Frontier cooperative wells (including 520 ft of core), combined with geologic characterization of the Frontier throughout a study area that encompassed the area of greatest operator activity, led to GRI's drilling of SFE No. 4 in 1990. Specifically targeted was the Second Bench of the Second Frontier, which extends the length of the Moxa Arch and contains the most prolific Frontier gas reservoirs in the western Green River Basin. The SFE No. 4 well was drilled in Chimney Butte field, Sublette County, through the Frontier Formation to a depth of 8,100 ft. A total of 323 ft of core was recovered.

Research was extended in 1990 to include the Pennsylvanian Canyon Sandstone in southwest Texas, where the efficiency of burgeoning operator activity was being impeded by lack of information on regional and reservoir geology. Regional geology of the Canyon was investigated in a five-county (Schleicher, Sutton, Edwards, Val Verde, and Crockett) study area in the Val Verde Basin and Ozona Arch—mapping of structure and sandstone geometry, construction of detailed stratigraphic cross sections, and description and interpretation of core from Sawyer and Sonora fields in Sutton County.

The Pennsylvanian Cleveland Formation had been considered as a candidate for the SFE No. 4 well and, due to continued operator interest in geologic framework studies, a stratigraphic study of the formation was undertaken in a seven-county (Hansford, Ochiltree, Lipscomb, Hutchinson, Roberts, Hemphill, and Wheeler) area of the Anadarko Basin. Mapping of structure, formation thickness, and sandstone thickness was used to delineate reservoir distribution of this progradational clastic system, interpret depositional history, and characterize component facies.

In 1990 a screening process was initiated for choosing an appropriate low-permeability formation for the proposed GRI hydraulic fracture test site facility. A national screening of low-permeability formations was conducted by the Bureau to identify units that met the criteria for the test site. In the course of this work data from cooperative wells and a GRI research well were collected and analyzed.

By 1991, simultaneous studies were under way in the Frontier, Canyon, Davis, and Cleveland sandstones, and limited studies or reviews of other formations were in progress in support of proposed engineering experiments. These wide-ranging studies, together with previous work on the Travis Peak, Corcoran–Cozzette, and Cotton Valley set the stage for preparing a national survey of the depositional history, reservoir distribution, diagenesis, structure, in situ stress, engineering attributes, and production of 24 leading low-permeability sandstone reservoirs. This work was summarized in Bureau of Economic Geology Report of Investigations No. 211.

The final phase of research on this project focused on development and validation of new concepts that allow accurate prediction of the location of open, potentially conductive natural fractures within sedimentary basins and new methods to measure key geologic variables influencing production in stratigraphically and diagenetically complex reservoirs. Some preliminary results of this work have been transferred to industry.

Research Approaches

A multidisciplinary approach to formation evaluation is the most accurate for assessing reservoir properties. This section summarizes some of the elements that have been found to be critical in characterizing low-permeability sandstone reservoirs.

Our geologic studies can be divided into (1) stratigraphy and depositional systems, (2) reservoir composition and diagenesis, and (3) structural history, structural geometry, natural fractures, and stress attributes. Information on each of these topics is necessary to completely characterize any tight formation geologically, yet it is important to recognize that the objects of these studies are commonly interrelated. Information from one area often provides important insight into solutions to seemingly unrelated problems in other areas, as illustrated by the use of diagenetic information to improve understanding of natural fractures (topical report GRI-94/0455).

Stratigraphic information explains the physical framework in which the gas resource exists. Depositional history determines the regional distribution, geometry, and texture of the reservoir sandstones, as well as the characteristics of the nonreservoir facies that may act as barriers to vertical growth of hydraulic fractures resulting from high in situ stress. Production characteristics of tight gas reservoirs are partly controlled by diagenetic modifications to the reservoirs; extensive cementation is commonly why permeability is low. Finally, studies of structural history and geometry, natural fractures, and stress attributes are important to the understanding of tight gas resources because hydraulic fracture treatments are commonly carried out to achieve economic flow rates. Horizontal drilling is a promising method for developing low-permeability gas reservoirs. Determining the present stress state in reservoir rocks and adjacent strata helps the direction of hydraulic fracture propagation to be predicted and fractures to be contained more effectively. In addition to potentially providing conduits for fluid flow to the wellbore, the abundance and orientation of natural fractures may affect the orientation and shape of hydraulic fractures and influence fluid leakoff characteristics.

Stratigraphy and Depositional Systems

A *depositional system* is a group of lithogenetic facies linked by depositional environment and associated processes. In other words, it is a group of rock strata that were deposited in closely associated sedimentary environments. Depositional systems are the stratigraphic equivalent of major physical geomorphic units, such as modern rivers or deltas. The depositional system can be divided into its component genetic *facies*, which are three-dimensional rock bodies characterized by specific sand-body geometries, lithologies, sedimentary structures, and initial porosity and permeability. Understanding at the facies level is a goal of stratigraphic analysis because commonly at the facies scale the basin's fluid migration pathways, including those of gases and connate waters, are established. A particular facies will have similar characteristics no matter where it has been deposited as long as energy conditions, processes, available sediment supply, and accommodation space were relatively uniform. Thus, classifying tight gas sandstones by their depositional systems and component facies establishes a framework for comparison among stratigraphic units of different ages in different sedimentary basins. Unlike details of a stratigraphic sequence, which may vary between and within basins, characteristics of genetic facies tend to remain constant within a range determined by conditions of deposition. This classification helps provide a basis for determining the extent to which geologic and engineering knowledge gained in the study of one formation can be applied to the study of another.

Nine principal clastic depositional systems can be classified into continental, shoreline (marginal marine), and marine environments, and the nine systems can be subdivided further. For example, the fluvial system can be divided into braided streams, fine-grained meanderbelts, coarse-grained meanderbelts, and stabilized distributary channels. Each of these subclasses has distinctive sand-body geometry, texture, and distribution of internal sedimentary structures. Similarly, deltas can be divided into river-dominated types that have digitate to lobate geometries and into wave-dominated types that have cuspate geometries.

The thickness of a sandstone depends on sediment supply, water depth, and rate of basin subsidence. Thick sandstones generally form when the products of repetitive depositional events stack vertically, which introduces layering that can be detrimental to hydraulic-fracture stimulation. The amount of sediment input, basin subsidence, and sea-level changes are the main factors that control the vertical sequence of deposits. Clean (low clay content) sandstones, which generally make the best reservoirs, are deposited in environments where physical processes cause segregation of the bed-load (sand and gravel) and suspended-load (silt and clay) components of the sediment dispersal system. The high energy of the river channel or marine shoreface (the narrow zone affected by wave action) efficiently segregates the coarse and fine sediment fractions. Processes at the distributary mouth bar of delta systems are also efficient sediment sorters. The cleanest shales (having the lowest sand and silt content), which are the best barriers to hydraulic-fracture growth, form in quiet, low-energy environments, such as a lagoon or deep-marine basin. Transitional environments are common between the zones of highest and lowest energy, in which muddy sandstones and sandy mudstones are deposited. Only in special cases (during marine transgression, for example) are the clean sandstones that make the best reservoirs bounded by thick shale deposits that make the best barriers to fracture growth. The stress contrast between reservoir sandstones and the overlying and underlying beds is critical to hydraulic-fracture design, and rock mechanical properties of these beds can vary as a result of subtle contrasts in rock composition and texture.

Reservoir Composition and Diagenesis

Original porosity and permeability of sandstones are determined by their depositional environment, but diagenesis can significantly alter reservoir characteristics after deposition. Most tight gas reservoir sandstones had moderate to high porosity and permeability at the time of deposition, but compaction and precipitation of authigenic mineral cements from aqueous pore fluids during burial have destroyed much of the original intergranular (primary) porosity. Older and deeper sandstones typically have lower porosity than do younger or shallower sandstones because they have undergone more extensive compaction and cementation. The importance of time for these porosity-reducing reactions to occur is evident from the age of most of the tight gas sandstones in the United States, which are Paleozoic (570 to 245 Ma) or Mesozoic (245 to 66 Ma). The only major Tertiary (66 to 1.6 Ma) tight gas sandstones are the Wilcox and Vicksburg of the Texas Gulf Coast, which have been deeply buried.

In addition to providing information on porosity and permeability distribution, study of the mineral composition of tight gas reservoirs is necessary for calibrating the log response of the reservoir and adjacent nonreservoir rocks in the formation. Composition and volume of detrital grains, clay matrix, and authigenic cements, as well as the type of pores, size of pore throats, and distribution of clays are correlated to log response and petrophysical properties such as permeability, porosity, pore-throat diameter, water saturation, and rock strength.

Information on the composition and distribution of minerals and pores in tight gas sandstones is derived primarily from thin-section point counts, X-ray diffraction analysis, and scanning electron microscopy (SEM). Framework-grain composition of a sandstone is typically expressed as the ratio of quartz:feldspar:rock fragments (QFR), which are the "essential grains" that are used to classify a sandstone. Quartz is the most abundant detrital mineral in most sandstones. If other minerals, such as feldspars or metamorphic rock fragments composed dominantly of mica, are unusually abundant, log analysts take this into account by using a different grain density. An abundance of feldspar grains, many of which are unstable and dissolve in the burial environment, may indicate that secondary porosity affects the porosity network. Abundant rock fragments, particularly metamorphic and sedimentary rock fragments, may indicate that the sandstone has undergone loss of porosity by ductile grain deformation.

Petrographic analyses of framework mineralogy, porosity, clay content, and clay distribution reveal compositional controls on rock strength. This information can then be combined with well-log analyses to yield fairly accurate predictions of rock strength and mechanical properties in treatment intervals and potential fracture barriers.

Fluid and gas in a sandstone flow most readily through well-connected, intergranular pores. In most tight gas sandstones, the intergranular pore network has been almost completely occluded by precipitation of authigenic cements. The result is that narrow, slot-like apertures between pores provide the major connectivity for fluid flow, and these narrow slots are closed easily by increasing pressure (effective stress). Thus, to measure permeability in tight gas sandstones accurately, one must analyze core under net overburden pressure conditions (stressed permeability), not at ambient surface pressure (unstressed permeability).

In many tight gas sandstones, the most abundant macropores (pores having pore-aperture radii of >0.5 μm) are secondary pores formed by dissolution of detrital grains, particularly feldspars. Secondary pores provide pore volume for gas storage, but they generally are connected only by the remaining narrow, intergranular pores. Therefore, permeability in tight gas sandstones containing mostly secondary pores is still controlled by the highly occluded intergranular pore network. Micropores (pore-aperture radii of >0.5 μm) are common in some tight gas sandstones, such as the Frontier Formation in the Green River Basin, but microporosity contributes little to permeability. Formations that have abundant microporosity may be interpreted from logs as having high porosity, but they have low permeability.

Tight sandstones can be divided on the basis of pore geometry into (1) sandstones that have open intergranular pores whose pore throats are plugged by authigenic clay minerals, (2) sandstones that have intergranular pores that have been largely occluded by authigenic cements (mainly quartz and calcite) and reduced to narrow slots that connect large secondary pores formed by grain dissolution, and (3) muddy sandstones that have intergranular volumes filled by detrital clay matrix and porosities that are mainly microporosities. According to recent surveys, Type 2 sandstones are the most common tight gas reservoirs, and most of the 24 sandstones in the 1993 atlas are Type 2 [29]. Sandstones that are exclusively Type 1 are rare, but many of the formations discussed in this atlas are Type 2 sandstones that also contain authigenic clays plugging pore throats. The poorest reservoirs in many low-permeability formations are Type 3 sandstones, and they probably do not contribute significantly to total gas production. The low-permeability, downdip part of the Olmos Formation is an example of a Type 3 sandstone. Type 3 sandstones are poor reservoirs because they have low porosity and permeability from the time of deposition as a result of an abundance of detrital clay that was either deposited with the sand or mixed in shortly after deposition by burrowing. Compaction further reduces porosity, so that Type 3 sandstones typically have no visible macroporosity. Although log-measured porosity may be as high as 10 percent, the porosity is all microporosity, and the sandstone has very low permeability.

Diagenetic complexity in Type 2 low-permeability sandstones varies considerably; the Travis Peak provides an example of a relatively simple system. There, although sandstones contain many different authigenic minerals, quartz is the most abundant porosity-occluding cement. As the volume of quartz cement increases with increasing burial depth, the volume of intergranular primary porosity decreases and permeability also decreases. Average porosity and permeability can be predicted by depth in this formation. The Frontier Formation in the Green River Basin is a more complicated system. Quartz cement is the main control on porosity in some areas along the Moxa Arch, but in other areas calcite cement dominates. As a result, no trend emerges in either porosity or permeability with burial depth.

Authigenic clay minerals have an effect on the producibility of tight gas sandstones beyond simple porosity reduction. Because of their high surface-to-volume ratio, clays increase water saturation, which decreases relative permeability to gas. The relative influence on permeability of the main types of clay minerals varies in tight gas sandstones. Kaolinite generally occurs in compact clusters inside secondary pores, so it has the least effect on permeability. Chlorite flakes commonly line primary pores and thus have an influence greater than kaolinite of decreasing permeability. Illite and mixed-layer illite-smectite occur as fibers that have high surface areas and thus the greatest effect in reducing permeability. The presence of fibrous illite in a sample can jeopardize accurate permeability measurements from core plugs. Conventional core analysis of illite-bearing sandstones can indicate unrealistically high permeabilities caused by the collapse of illite fibers during drying.

Clay minerals in sandstones can also cause production problems because they are sensitive to completion fluids. Iron-rich chlorite will react with acid and form iron hydroxides that reduce permeability if the treatment liquids are not properly chelated. Swelling clays, such as smectite or mixed-layer illite-smectite with a high percentage of smectite layers, are sensitive to fresh water. Many of the 24 formations reviewed by Dutton and others in RI 211 have a high percentage of illite layers, and thus they are not very sensitive to fresh water. A more difficult problem is reducing the permeability that results when water saturation increases as a result of drilling or stimulating a low-permeability formation.

Natural Fractures and Structure

Most rocks near the earth's surface (<3 to 6 mi deep) are brittle materials. Under the influence of extension, compression, flexure, uplift, cooling, and fluid migration, many rocks acquire networks of fractures of various types and sizes. Reservoir rocks may contain both opening-mode fractures and faults that range from microfractures normally only visible under the microscope to large fractures and faults thousands of feet in size.

Natural fractures are commonly observed in core from low-permeability-sandstone reservoir rocks, although many of these fractures are nearly vertical and therefore scarcely prone to intersection by vertical boreholes. Fractures are thus locally abundant in the subsurface, even in areas distant from structural perturbations such as folds and faults. In many cases, these fractures have been open or partly open in the subsurface, and locally they are associated with abrupt inflows of gas into the wellbore. Fractures in several of low-permeability reservoirs have become targets for horizontal drilling.

Knowledge of fracture occurrence, orientation, and pattern is important for engineering evaluation and development of reservoirs having low matrix permeability and for correct placement of horizontal wells designed to cross fractures. Natural fractures likely play a key role in production from parts of most, if not all, low-permeability-sandstone reservoirs based on the disparity observed in some reservoirs between permeability measured on core samples and that implied by production histories. Fractures having marked effects on reservoir performance have been described from the Cotton Valley sandstone in the East Texas and North Louisiana basins, the Mesaverde in the Piceance Basin, the Frontier Formation in the Green River Basin, and the Davis Sandstone in the Fort Worth Basin, among others.

In addition to providing pathways for fluid movement locally, engineering analyses have also confirmed geologic predictions that natural fractures can profoundly affect the way induced hydraulic fractures grow. The growth of multiple fracture strands in naturally fractured intervals has been postulated to reflect pressure anomalies detected during hydraulic fracture treatments.

Although regional fractures commonly occur in subparallel sets, sets generally show variable spacing and patterns may change gradually or abruptly on both regional and local (field, interwell) scales. Fractures are arranged in networks that reflect the reservoir structure, the history of burial and tectonic loads that caused fracture propagation, and the evolving physical properties of the rock. Fracture-network interconnectivity and patterns of mineral fill within fracture networks control the size and shape of the rock volume contacted by a given borehole intersecting the network.

Faults are common geologic features that are a type of reservoir heterogeneity occurring in tight gas sandstones in a wide spectrum of sizes. Whereas large faults can compartmentalize reservoirs by juxtaposing reservoir and nonreservoir rocks, small faults may also be barriers to fluid flow as a result of grain breakage and porosity reduction, even where faults produce sandstone-on-sandstone contacts. Normal faults are common features of many Gulf Basin reservoirs such as the Lobo Wilcox and Vicksburg, and reverse and strike-slip faults are present in other plays. Data on faults in a given reservoir are commonly incomplete and affected by sampling bias. Faults with substantial throw are generally invisible on seismic lines, but data from infill wells, where available, is seldom adequate to illuminate fault patterns in areas distant from these wells.

Natural fracture analysis, too, is hindered by obstacles to fracture sampling. Even simple fracture network patterns are difficult to impossible to document using conventional methods in vertical boreholes: fractures commonly escape detection on logs or in core. Detailed information on fracture density, connectivity, and orientation patterns currently can be obtained only from outcrop studies of reservoir analogs (exposed reservoir-facies rocks having structural histories similar to target horizons). Well tests and other engineering tests have provided little insight into natural fracture systems; commonly oversimplified representations of fracture networks are used to interpret such tests, often obscuring the effects of natural fractures on well tests and long-term reservoir behavior.

The effect of fractures on production depends on, among other factors, the relative permeability, porosity, and interconnectivity of the fracture network compared with that of the matrix rock. The cumulative effect of long exposure to fracturing processes associated with tectonism, burial, uplift, and migrating fluids should work to produce an interconnected, conductive fracture network in older rocks. However, diagenetic processes of mineral precipitation tend to fill and close fractures. The intense faulting that characterizes the Tertiary (Eocene) Lobo Wilcox trend shows that such generalized models are no substitute for direct measurement of fractures and formation-specific predictive models.

As part of this project, new methods have been introduced that allow site-specific information on fracture properties to be obtained from rock samples, even where visible fractures are not present. This work is partly described in topical report GRI-94/0455.

Stress

Stress directions and stress contrasts in low-permeability sandstone reservoirs are important to the design of engineering operations in these rocks. Because under typical reservoir conditions the growth direction of hydraulic fractures tends to parallel maximum horizontal stress (SHmax), knowledge of principal stress directions is necessary for effective placement and stimulation of wells. This information is also important where open natural fractures contribute to production because open fractures may be preferentially aligned parallel to SHmax.

The contrast in the magnitude of the minimum principal stress between different beds is one of the key factors governing the vertical growth of a hydraulic fracture. If hydraulically created fractures grow significantly taller in the vertical direction than specified in treatment design, then fracture width and length will be less than anticipated, and strata above and below the treatment interval may be inadvertently intersected by treatment fractures, which may damage the well.

Worldwide, most intraplate stresses are compressional, but a complex extensional stress province exists in the western United States: the Cordilleran extensional province. Such provinces commonly have elevated topography and heat flow. The Cordilleran province also comprises several domains having contrasting directions of maximum horizontal stress. This variability in stress orientation and the limited resolution of regional stress-direction maps that arises from sparse well data make stress directions in some western basins challenging to predict. For example, evidence conflicts about stress directions from the Frontier Formation in the Green River Basin. Stress directions in the formations studied in this project have been determined using several methods. One of our roles has been to synthesize and interpret test results in their geologic and tectonic context and according to the rock's composition and microstructure.

Synopsis of Research Results

In addition to developing general principles that apply to many formations, this project has produced specific, in-depth geological and reservoir-property analyses of several important low-permeability reservoir formations.

East Texas Studies: Travis Peak Formation

The main goal of the geologic studies of the Tight Gas Sands Program in East Texas was to document the geologic framework of the Travis Peak Formation. Insights gained from this multifaceted study increased understanding of the geologic controls on distribution and behavior of Travis Peak tight gas reservoirs. Geologic studies in East Texas thoroughly characterized low-permeability gas reservoirs by determining (1) the size, orientation, and distribution of reservoir sand bodies, (2) the mineral composition of reservoirs and their response to geophysical logs, (3) the variability in porosity and permeability with depth, (4) natural fracture occurrence and orientation, and (5) the direction of in situ stress, which controls hydraulic fracture propagation. In addition to reaching specific conclusions about the Travis Peak, this study also provided a methodology for future geologic studies of other low-permeability, gas-bearing sandstones. Stratigraphic, petrographic, and structural studies formed the three main areas of geologic investigation that were needed to characterize this tight gas sandstone. The annotated bibliography lists reports that describe these results in detail.

Green River Basin: Frontier Formation

The main goal of the geologic studies of the program in the Green River Basin, Wyoming, was to document the geologic framework of the Frontier Formation. Insights gained from this multifaceted study increased the understanding of geologic controls on the distribution and behavior of the Frontier tight gas reservoir. The annotated bibliography lists reports that describe these results in detail.

Val Verde Basin: Canyon Sandstone

The objective of the geologic study of the Canyon Sandstone formation was to develop a comprehensive description of the physical characteristics of the reservoir sandstones and new methods to map stratigraphically complex outer shelf sandstones. To accomplish this task, it was necessary to (1) map regional and field-scale Canyon sandstone distribution, (2) interpret and characterize depositional systems and facies, (3) investigate how the diagenetic history of the sandstones has modified reservoir porosity and permeability, and (4) summarize observations of natural fractures in Canyon core. Results are described in several reports and papers (see annotated bibliography).

North Texas/Oklahoma: Cleveland Formation

Low-permeability sandstones of the Upper Pennsylvanian (lower Missourian) Cleveland Formation compose major gas-producing reservoirs in the western Anadarko Basin of the northeastern Texas Panhandle. Although Cleveland reservoirs had produced >435 Bcf of natural gas as of January 1991 (according to Railroad Commission of Texas reports) and have an estimated 38 Tcf of gas in place, little published information is available on even the basic geology of the unit. The topical report on the Bureau's Cleveland study, which was distributed to GRI in November 1992, and other publications offer a firm geologic basis for other subregional and field-specific studies of the Cleveland. The annotated bibliography lists these reports.

Rio Grande Embayment: Wilcox Lobo Formation

The objective of the geologic study of the Wilcox Lobo Formation was to develop a comprehensive description of the physical characteristics of the reservoir sandstones. The results of studies completed at this time are summarized in the annotated bibliography.

New Methods to Evaluate Natural Fractures

The aim of the project is to provide unique information about subsurface fracture properties in sandstone at low cost. New methods can identify fractured zones, measure fracture orientation, and determine if fractures can conduct fluids based on analysis of microfractures in conventional whole core or drilled (rotary) sidewall core samples. Using wireline sampling (sidewall cores) can greatly reduce costs. The methods are simple to use and can produce analytic results in a few days. Results can be used to identify zones with conductive fractures (thief zones, sweetspots) and to design horizontal wells to contact or avoid fractured areas, and thus the methods have applications to exploration, development, and reservoir management. These methods are a breakthrough over conventional techniques for the following reasons.

Despite improvements in detection and characterization of large fractures with geophysical logging tools and seismic methods, subsurface fracture properties are often conjectural because large fractures rarely intersect wellbores where they can be observed. In shallowly dipping petroleum reservoirs and hydrocarbon storage facilities, the lack of adequate sampling results from the vertical attitude of most wells and fractures and the wide (>1 m) spacing of large fractures. Consequently, it is common that many fracture attributes that critically affect hydraulic and mechanical properties of subsurface rocks are unknown.

In many sandstones, microfractures, with sizes of microns to millimeters, are more common than large fractures and can be sampled effectively even in small volumes of rock. However, the types of microfractures that reliably provide information about large fractures are nearly invisible using conventional analysis methods. Our approach images these microfractures using high-resolution photomultiplier-based electron-beam-induced cathodoluminescence (scanned CL). Yet imaging microfractures is only one step in the process of using microfractures to diagnose the properties of large fractures. We are using imaging together with new fracture classification schemes, novel applications of conventional petrogenetic analysis, and advanced mathematical scaling methods to obtain high resolution (bed-by-bed) information on fracture orientation, conductivity, and other fracture properties. The key advantage is that the approach works without measuring elusive large, difficult-to-sample macrofractures.

Many technical issues have now been identified but remain to be resolved before the technique can be recommended for commercial deployment. Among these the following are crucial. How does rock composition, burial history, proximity to large fractures, and variable microfracture abundance affect accuracy, reliability, and cost of analysis? Are there rock types and areas where the method should not be deployed or where special sampling approaches are needed? What sampling density, laboratory techniques, and analytical methods give the most reliable and cost-effective results? What are costs and turnaround times for the procedure? What additional information about macrofractures can be learned? Can macrofracture conductivity be quantified and accurately mapped? Can multiple fracture sets and connectivity be diagnosed?

Initial results are very promising. Our plans called for completing six case studies to address these technical issues and to document the power and cost effectiveness of the approach for measuring fracture orientations, if we receive support from industry to continue the work. We believe this approach can have direct and immediate benefits for operators by allowing economic characterization of fractured sandstones that cannot be achieved in any other way.

National Surveys

The Bureau Report of Investigations No. 211 summarizes geologic, engineering, and production information for 24 low-permeability, natural gas-bearing sandstone reservoirs in 13 basins in the United States. The 24 low-permeability formations in the report were selected either because they contain abundant natural gas reserves and resources or because the geologic and engineering data available for their characterization could apply to other, similar gas-bearing formations. This report updates an earlier summary of low-permeability sandstones by Finley titled *Geology and Engineering Characteristics of Selected Low-Permeability Gas Sandstones: A National Survey.*

Review of Technology Transfer Success

Measuring the success of the dissemination of information is challenging. How and to what extent ideas, concepts, models, and specific facts about formations and reservoirs are acquired by the producer community, how they are perceived, and how they are used, are often difficult to judge quantitatively. Although improving methods to assess technology transfer success is a worthwhile goal (because it can lead to enhanced utilization of research results), it is beyond the scope of this report. However, we do present a few readily available measures of information transfer success showing that the results of our studies have been made available to the public.

Over the course of the project, topical reports, the Bureau of Economic Geology publications series, published papers, oral presentations, and workshops have been used to communicate research results to industry and the general scientific community: 29 Gas Research Institute topical reports and more than 102 other published works. Nine Bureau Reports of Investigations and one Geological Circular have been published by the Bureau of Economic Geology. These reports and papers describe preliminary findings, summarize specific experiments and studies, and present final results of completed studies. In addition to these publications and for the purpose of facilitating engineering research activity, the Bureau also produced numerous written documents that are not formal publications, including preliminary geologic description reports and other documents describing core and other data collected in SFE and cooperative wells. Shortly after data collection, these reports were issued to other GRI contractors and to companies and operators involved in cooperative wells.

Topical reports communicate results efficiently because they are distributed directly to industry users, appear as part of a set of GRI project publications, and are made available through GRI's publication distribution system. The Bureau has contributed to GRI reports on SFE wells, which describe integrated reservoir characterization and engineering case studies in experimental wells.

The publication series of the Bureau of Economic Geology is advertised nationally to a mailing list of about 7,500 subscribers. More than 145 libraries and other geological surveys receive Bureau publications in cooperative exchange-of-publications agreements. Bureau publications are also distributed through over-the-counter sales. Over-the-counter sales of publications developed in the Tight Gas Sands Project have been steady. By 1996, more than 1,500 project-related BEG publications had been sold.

Another important medium for information transfer is peer-reviewed journals. These publications reach a wide international audience that includes not only other researchers but also key management personnel in industry who directly influence the resource development strategies and field operations that are used in their companies. Bureau workers have published 18 articles in peer-reviewed journals on topics directly related to work conducted on the tight gas project. On the basis of a conservative circulation estimate of 10,000 for each of these journals (for example, AAPG Bulletin circulation is 33,500), we estimate that these articles have reached a substantial part of the scientific community.

More than 67 professional presentations, of which papers or abstracts would be published, were given concerning the Bureau's project research. Many of these were presented at large national or international conventions, where audiences can be substantial. We estimate that these presentations reached an audience of 6,000 engineers, geologists, and managers.

A total of 83 presentations that had no published papers or abstracts were made on various aspects of the Bureau's tight gas sandstone research. Many of these were given at local geological societies whose members actively explore and produce tight gas sandstones and thus can immediately apply information and technology developed through the GRI program. An additional 23 talks were presented in GRI and other workshops. We estimate that these talks and workshops of GRI-sponsored Tight Gas Sands research reached an audience of 4,000 geologists and engineers.

Direct discussions with industry workers, although informal, can convey a quantity of information developed in the project. Although fewer people are reached directly by these means than by publication and formal presentation, interpersonal communication commonly solves specific geologic and engineering problems.

Additionally, because of continuing research on this topic at the Bureau and the steady distribution of research results, the Bureau is perceived as a source of tight gas sand geologic information. Through telephone conversations, letters, visits, and informal meetings, the Bureau receives inquiries concerning specific tight gas reservoirs, fields, or wells, regional or basinwide geologic frameworks, and analytical techniques for characterizing tight gas sands. On average, Bureau workers involved in tight gas sands research receive three to five telephone or letter inquiries per month. Many of these inquiries lead to office visits during which research results are reviewed and discussed in depth. Because the project typically involves about four Bureau scientists, informal industry contacts average 200 to 250 per year.

The project has been singled out for several professional and technical awards. The paper *Petrography and Diagenesis of Lower Cretaceous Travis Peak (Hosston) Formation, East Texas*, which was presented at the 1986 annual meeting of the Gulf Coast Association of Geological Societies received the First Place Best Paper award and the A. I. Levorsen Memorial Award for excellence in presentation. The paper *Organic Geochemistry of the Lower Cretaceous Travis Peak Formation, East Texas Basin*, which was presented at the 1987 annual meeting of the Gulf Coast Association of Geological Societies, also received the First Place Best Paper award and the A. I. Levorsen Memorial Award. A paper titled *Fracture Trace Maps of Upper Cretaceous Pictured Cliffs Sandstone Pavements*, which describes fracture studies of tight gas sandstones, and which was presented at the American Association of Geologists Annual Meeting, was awarded the AAPG Energy Minerals Division President's Certificate for Excellence in Presentation. Finally, a paper titled *Fracture Detection in Low-Permeability Reservoir Sandstone: A Comparison of BHTV and FMS Logs to Core*, presented at the 1988 Society of Petroleum Engineers Annual Technical Conference in Houston, October 2–5, 1988, was chosen for presentation in the Best of SPE for AAPG session at the 1989 Annual Meeting of the American Association of Petroleum Geologists.

An Annotated Summary of Project Publications

Gas Research Institute Topical Reports

East Texas Studies

Geology of the Lower Cretaceous Travis Peak Formation, East Texas—depositional history, diagenesis, structure, and reservoir engineering implications: by Dutton, S. P., Laubach, S. E., Tye, R. S., Baumgardner, R. W., Jr., and Herrington, K. L., 1990, The University of Texas at Austin, Bureau of Economic Geology, topical report no. GRI-90/0090 prepared for the Gas Research Institute under contract no. 5082-211-0708, 170 p.

This report summarizes stratigraphic, petrographic, and structural studies of the Lower Cretaceous Travis Peak Formation, a low-permeability gas sandstone in East Texas, and presents reservoir engineering implications. Depositional systems in this region were interpreted from logs and cores and include (1) a braided- to meandering-fluvial system that forms the majority of the Travis Peak section, (2) deltaic deposits interbedded with the distal part of the fluvial system, (3) paralic deposits that overlie and interfinger with the deltaic and fluvial deposits near the top of the Travis Peak, and (4) shelf deposits present at the downdip extent of the formation. Petrographic studies indicate that the sandstones are quartzarenites and subarkoses. Cementation by quartz, dolomite, ankerite, illite, chlorite, and reservoir bitumen has reduced porosity to <8 percent and permeability to <0.1 md throughout most of the formation. Structurally deeper sandstones are more intensely quartz cemented than are shallower sandstones and contain abundant, open natural fractures. Borehole breakouts and drilling-induced fractures in core can be used to predict horizontal stress directions and the direction of hydraulic fracture propagation. Hydraulic fractures propagate in directions subparallel to the east-northeast strike of the natural fractures; thus, hydraulically induced fractures may not intersect many natural fractures.

Analysis of natural fractures and borehole ellipticity, Travis Peak Formation, East Texas: by Laubach, S. E., Baumgardner, R. W., Jr., and Meador, Karen, 1987, The University of Texas at Austin, Bureau of Economic Geology, topical report no. GRI-87/0211 prepared for the Gas Research Institute under contract no. 5082-211-0708, 128 p.

This report summarizes petrographic studies of natural and coring-induced fractures in 7 cores from the Travis Peak Formation, a low-permeability gas sandstone in East Texas, and also presents an analysis of fracturing and wellbore elongation based on borehole televiewer, Formation Microscanner, and ellipticity logs from 12 Travis Peak wells. Natural vertical extension fractures in sandstone are open or only partly mineral filled in the cored depth range (~–5,000 to –10,000 ft), and they are therefore potential gas reservoirs as well as a potentially important influence on commercial hydraulic fracture treatment. Crack-seal structure in fracture-filling quartz shows that fracturing and quartz cementation were contemporary; this result, together with evidence of timing of fracturing and the large water volumes that are inferred to have passed through the Travis Peak, suggests that elevated pore-fluid pressures enhanced fracture development. Healed transgranular microfractures that occur in sandstone can be used to ascertain natural fracture trends in core that lacks macrofractures, and coring-induced petal-centerline fractures can be used to infer stress orientations. Fractures trend east-northeast to east. In the upper Travis Peak, borehole ellipticity trends east-northeast, parallel to fracture trends, and in the lower Travis Peak ellipticity trends north-northwest, parallel to the direction of least horizontal stress. This preliminary report presents initial data and conclusions that were developed in subsequent work and reported in Bureau Report of Investigations No. 185 and various journal publications.

Application of borehole-imaging logs to geologic analysis, Cotton Valley Group and Travis Peak Formation, GRI Staged Field Experiment wells, East Texas: by Laubach, S. E., Hamlin, H. S., Buehring, Robert, Baumgardner, R. W., Jr., and Monson, E. R., 1990, The University of Texas at Austin, Bureau of Economic Geology, topical report no. GRI-90/0222 prepared for the Gas Research Institute under contract no. 5082-211-0708, 115 p.

This report summarizes studies of two geophysical logging tools, the borehole televiewer and the Formation Microscanner, that were used in GRI's three Staged Field Experiment wells and in a cooperative well in East Texas. These tools can detect natural fractures and induced fractures that reflect in situ stress conditions, as well as lithologic features that can be important for geologic interpretation. Improvement in borehole televiewer and Formation Microscanner technology has been rapid in the past several years, but calibration of the logs with core is needed to ensure accurate interpretations of the logs. Our study compares borehole televiewer and Formation Microscanner logs with core from wells in low-permeability gas reservoir sandstone. Vertical fractures in Travis Peak and Cotton Valley sandstone usually are visible on borehole televiewer and Formation Microscanner logs, but some fractures were missed or are indistinct. Aspects of fracture shape can be determined and fractures can generally be separated from borehole breakouts, but natural fractures are difficult to distinguish from some types of drilling-induced fractures on either log. Fracture orientation is readily obtained for inclined fractures from either borehole televiewer or Formation Microscanner logs, but the orientation of vertical fractures, the common fracture type in East Texas reservoirs, can be ambiguous locally on both logs. Formation Microscanner images can be used to help document and interpret depositional environment, and they provide images of sedimentary structures and thin beds.

The Travis Peak (Hosston) Formation: geologic framework, core studies, and engineering field analysis: by Finley, R. J., Dutton, S. P., Lin, Z. S., and Saucier, A. E., 1985, The University of Texas at

Austin, Bureau of Economic Geology, topical report no. GRI-85/0044 prepared for the Gas Research Institute under contract no. 5082-211-0708, 233 p.

Because this was the first Bureau topical report on the Travis Peak Formation, much of the information in it was updated and superseded in subsequent reports, particularly the regional stratigraphic interpretations (see GRI-88/0325 and GRI-90/0090).

The Travis Peak (Hosston) Formation constitutes a 1,000- to 5,000-ft-thick clastic wedge that formed two major depocenters along the north flank of the Gulf Coast Basin. The depocenters were dominated by fluvial-deltaic facies. A delta-fringe facies, including tidal flat and nearshore shallow-marine shelf facies, formed around the margins of the clastic wedge. These marginal-marine deposits within the upper Travis Peak are the most productive facies of the formation within a nine-county area in East Texas.

Sandstones in the Travis Peak are mineralogically mature. Low permeability and occlusion of porosity is primarily due to quartz overgrowths, authigenic clay, ankerite, and reservoir bitumen, a high-molecular-weight hydrocarbon residue. Within six Travis Peak gas fields in East Texas, porosity ranges from 8 to 11 percent and water saturation ranges from 28 to 44 percent within intervals of net pay. The permeability-thickness product is low in the south part of the study area and increases toward the north. Upper limits of permeability range from 0.074 md (median value) to 0.084 md (thickness-weighted average), on the basis of well tests that postdate fracture treatment. Within Chapel Hill field, three reservoir sandstone types were defined; sandstones with greatest lateral continuity were deposited as sandy tidal flats, including associated channel sandstones that trend northwest. Lower energy tidal-flat deposition is characterized by increased mud content of sandstones, and local marine transgression resulted in deposition of mudstone and muddy limestone.

Diagenesis and burial history of the Lower Cretaceous Travis Peak Formation, East Texas: controls on permeability in a tight gas sandstone: by Dutton, S. P., 1987, The University of Texas at Austin, Bureau of Economic Geology, topical report no. GRI-87/0079 prepared for the Gas Research Institute under contract no. 5082-211-0708, 158 p.

Petrographic and geochemical studies were used to determine the diagenetic and burial history of Travis Peak sandstones in East Texas and to relate the diagenesis to permeability variations within the formation. Permeability in much of the formation has been reduced to less than 0.1 md by compaction, cementation, and minor pressure solution.

Travis Peak sandstone is quartzarenite and subarkose, having an average composition of $Q_{95}F_4R_1$. The first authigenic cements to precipitate were illite, which coated detrital grains with tangentially oriented crystals, and dolomite. Next, extensive quartz cement, averaging 17 percent of the rock volume in well-sorted sandstone, occluded much of the primary porosity. Quartz is most abundant in the lower Travis Peak, in well-connected sandstone beds that were deposited in braided streams. Dissolution of orthoclase and albitization of plagioclase followed quartz cementation and occurred prior to mid-Cretaceous movement of the Sabine Uplift. Illite, chlorite, and ankerite precipitated after feldspar diagenesis. Oil migrated into Travis Peak reservoirs in the Late Cretaceous from Jurassic source rocks. Later deasphalting of the oil filled much of the remaining porosity in some zones near the top of the formation with reservoir bitumen.

Petrography and diagenesis of the Travis Peak (Hosston) Formation, East Texas: by Dutton, S. P., 1985, The University of Texas at Austin, Bureau of Economic Geology, topical report no. GRI-85/0220 prepared for the Gas Research Institute under contract no. 5082-211-0708, 71 p.

This preliminary report on the diagenesis of the Travis Peak Formation presents the results of petrographic studies based on data from 10 cores. The petrographic results are used to interpret the diagenetic history of Travis Peak sandstones and to relate the diagenetic history to permeability variations within the formation. Tables of petrographic data for 187 thin sections are included in the report, as are plates of photomicrographs that display characteristic features of Travis Peak sandstones. Many of the conclusions in this report are preliminary and were modified and documented more thoroughly in the later topical report GRI-87/0079 (following).

Comparative engineering field studies and gas resources of the Travis Peak Formation, East Texas Basin: by Lin, Z. S., and Finley, R. J., 1986, The University of Texas at Austin, Bureau of Economic Geology, topical report no. GRI-86/0016 prepared for the Gas Research Institute under contract no. 5082-211-0708, 96 p.

Data from eight fields producing from the Travis Peak Formation in the eastern East Texas Basin were used to define key engineering parameters for each field and to develop resource-reserve estimates. Field-average porosities range from 8 to 11 percent, and the median permeability for 191 wells is 0.088 md; field-average permeability ranges from 0.006 to 0.1 md. Gas productivity generally increases from south to north across the area studied with changes in the reservoir drive mechanism. Gas in place in the Travis Peak of the East Texas Basin is estimated to be 19.5 Tcf, assuming 12 percent of the area of the basin is ultimately productive.

Stratigraphy and depositional systems of the Lower Cretaceous Travis Peak Formation, East Texas Basin: by Tye, R. S., 1989, The University of Texas at Austin, Bureau of Economic Geology, topical report no. GRI-88/0325 prepared for the Gas Research Institute under contract no. 5082-211-0708, 80 p.

The Travis Peak Formation of the East Texas Basin was divided into five lithostratigraphic units. Formation of a fluvial-deltaic-paralic-shelf depositional systems tract was interpreted from analyses of stratigraphic and sedimentologic data that were acquired for each lithostratigraphic unit from well logs and cores. During early Travis Peak development, braided streams deposited channelbelt, floodplain, and overbank sediments in most of the study area. Downdip of the braided streams, deltas prograded to the south and southeast over a shallow, stable shelf. As braided streams migrated and enlarged, the site of deltaic deposition advanced southward and expanded to the northeast. Estuaries developed in relatively sediment-starved, embayed portions of the shoreline between centers of deltaic deposition. Seaward of the deltas, shelf sandstones accumulated through sediment-gravity processes triggered by high sediment loads and rapid deposition in the deltas.

Shoreline transgression and development of coastal-plain and paralic environments characterize late Travis Peak evolution. Fluvial systems transported a mud-rich sediment load and assumed a sinuous-braided to meandering form. Channelbelts coursed across a coastal plain with expansive floodplains and lakes and fed a few small retrogradational deltas. Estuaries enlarged and became a dominant coastal feature as submergence of the coastal plain progressed. With continued transgression, marine limestone of the Sligo Formation onlapped the Travis Peak.

Relationship between radar lineaments, geologic structure, and in situ stress in East Texas: by Baumgardner, R. W., Jr., 1988, The University of Texas at Austin, Bureau of Economic Geology, topical report no. GRI-88/0094 prepared for the Gas Research Institute under contract no. 5082-211-0708, 43 p.

Radar-based lineaments in East Texas and northwest Louisiana were studied to determine their relationship to surficial and subsurface geologic structure and to in situ stress. For all lineament data, two significant azimuths of vector sums were defined: 325° and 37°. The northwest trend has the same orientation as the mean direction of wellbore elongations in the Schuler Formation throughout the East Texas Basin. However, this trend is significantly different from the 344° orientation of wellbore elongation in the overlying Travis Peak Formation. These results suggest a complex relationship between subsurface stress and the northwest lineament trend. The northeast lineament trend does not coincide with the orientation of any known stress or regional structure and may be an artifact of radar illumination direction. Unlike a previous regional study based on smaller-scale Landsat data, no consistent correlation between surficial or subsurface structure and lineament density was discovered. However, high values of lineament density occur preferentially on outcrops of the Sparta and Weches Formations. These results suggest that either (1) most radar lineaments smaller than Landsat lineaments are manifestations of unmapped subregional or local structures or (2) most radar lineaments are surficial phenomena, unrelated either to subsurface geologic structure or to stress.

Landsat-based lineament analysis, East Texas Basin, and structural history of the Sabine Uplift area, East Texas and North Louisiana: by Baumgardner, R. W., Jr., and Jackson, M. L. W., 1987, The University of Texas at Austin, Bureau of Economic Geology, topical report no. GRI-87/0077 prepared for the Gas Research Institute under contract no. 5082-211-0708, 117 p.

The first half of this report documents the relationship between subsurface structure and lineaments in East Texas. More than 2,200 lineaments were mapped from 1:250,000-scale Landsat images. Vector sums of greater-than-average values of length-weighted frequency define significant peaks of lineament orientation. For all lineaments, significant peaks occur at 325° and 21°. The northwest peak parallels mean azimuth of borehole elongations in Cotton Valley sandstone wells throughout East Texas. Within the salt structure province of the East Texas Basin, lineament azimuth is not significantly different from salt structure azimuth. Lineament density delineates major fault zones.

The second part of this report describes new mapping of the stratigraphy and structure of East Texas and identifies the timing, extent, and orientation of arching episodes in the Sabine Uplift area, which is important in developing a structural history of the area. Estimation of movement on the Sabine Uplift was made from isopach maps of five Lower

Cretaceous units. The isopach maps show that the Sabine Uplift was not a horst during the Late Jurassic and Early Cretaceous but part of a large basinal area. Timing and magnitude of arching episodes on the uplift in the Mid-Cretaceous and early Tertiary indicate that the Sabine Uplift may have been produced by northeast-directed tectonic events in the Mexican Cordillera.

Geological analysis of the Travis Peak Formation: by Dutton, S. P., Fracasso, M. A., Laubach, S. E., Baumgardner, R. W., Jr., and Finley, R. J., 1988, *in* CER Corporation and S. A. Holditch & Associates, compilers and eds., Advancements in Travis Peak Formation evaluation and hydraulic fracture technology: Staged Field Experiment No. 1, Waskom field, Harrison County, Texas, topical report no. GRI-88/0077, prepared for the Gas Research Institute, p. 35–62.

Geological analyses of the Travis Peak Formation: by Laubach, S. E., Tye, R. S., Dutton, S. P., and Herrington, K. L., 1989, *in* Staged Field Experiment No. 2: application of advanced geological, petrophysical, and engineering technologies to evaluate and improve gas recovery from low permeability sandstone reservoirs, Travis Peak Formation, North Appleby field, Nacogdoches County, Texas: CER Corporation and S. A. Holditch and Associates, Inc., report no. GRI-89/0140 prepared for Gas Research Institute, p. 42–90.

Geological analysis of the Travis Peak Formation and Cotton Valley Sandstone: by Dutton, S. P., Laubach, S. E., Tye, R. S., Herrington, K. L, and Diggs, T. N., 1991, *in* Staged Field Experiment No. 3: application of advanced technologies in tight gas sandstones—Travis Peak and Cotton Valley Formations, Waskom field, Harrison County, Texas: CER Corporation and S. A. Holditch & Associates, Inc., topical report no. GRI-91/0048 prepared for the Gas Research Institute under contract no. 5090-211-1940, p. 27–66.

Frontier Formation

Geologic controls on reservoir properties of low-permeability sandstone, Frontier Formation, Moxa Arch, southwest Wyoming: by Dutton, S. P., Hamlin, H. S., and Laubach, S. E., 1992, The University of Texas at Austin, Bureau of Economic Geology, topical contract report no. GRI-92/0127 prepared for the Gas Research Institute under contract no. 5082-211-0708, 199 p.

This report examines the influence of stratigraphy, diagenesis, natural fractures, and in situ stress on low-permeability, gas-bearing sandstone reservoirs of the Upper Cretaceous Frontier Formation along the Moxa Arch in the Green River Basin, southwestern Wyoming. The main stratigraphic controls on distribution and quality of Frontier reservoirs are sandstone continuity and detrital clay content. The Frontier was deposited in a fluvial-deltaic system, in which most reservoirs lie in marine upper shoreface and fluvial channel-fill sandstone facies. The major causes of porosity loss in Frontier sandstones during burial diagenesis were mechanical and chemical compaction and cementation by calcite, quartz, and authigenic clays. Despite extensive diagenetic modification, reservoir quality is best in facies that had the highest porosity and permeability at the time of deposition. Natural fractures are sparse in Frontier core, but outcrop studies show that fractures commonly are in discrete, irregularly spaced swarms separated by domains having few fractures. Natural fracture swarms are potential high-permeability "sweet spots." Stress-direction indicators give highly scattered estimates of maximum horizontal compression direction ranging from north to east or northeast. The scatter may reflect interference of natural fractures with measurements of stress directions, as well as spatially variable stress directions and low horizontal stress anisotropy.

Geological analysis of the Frontier Formation: by Laubach, S. E., Dutton, S. P., and Hamlin, H. S., 1992, *in* CER Corporation, ed., Staged Field Experiment No. 4: application of advanced technologies in tight gas sandstones—Frontier Formation, Chimney Butte field, Sublette County, Wyoming: CER Corporation, topical report no. GRI-92/0394 prepared for the Gas Research Institute under contract no. 5091-221-2130, p. 25–90.

Stratigraphy and depositional systems of the Frontier Formation and their controls on reservoir development, Moxa Arch, southwest Wyoming: by Hamlin, H. S., 1991, The University of Texas at Austin, Bureau of Economic Geology, topical report no. GRI-91/0128 prepared for the Gas Research Institute under contract no. 5082-211-0708, 45 p.

By controlling sandstone continuity and detrital clay content, depositional systems influence reservoir development in low-permeability gas-bearing sandstones of the Upper Cretaceous Frontier Formation along the Moxa Arch in the Green River Basin, southwest Wyoming. Original depositional porosity and permeability are highest in clean Frontier sandstones, which even after diagenetic modification comprise the most prolific reservoirs. The Frontier was deposited in a fluvial-deltaic system, in which most reservoirs lie in fluvial channel-fill and marine shoreface sandstone facies. The fluvial channel-fill sandstones form southeast-trending belts, which are a few miles wide, several tens of feet thick, and separated by interchannel shale and sandy shale. Within the channel belts, clean sandstone occurs as discontinuous lenses as much as 20 ft thick that are interlayered and laterally gradational with mud-clast-rich shaly sandstone. The marine shoreface facies forms a continuous northeast-thinning sheet of sandstone, 40 to 120 ft thick. Clean sandstone is best developed near the top of the shoreface facies in northeast-thinning trends 5 to 40 ft thick.

Diagenetic controls on reservoir properties of low-permeability sandstone, Frontier Formation, Moxa Arch, southwest Wyoming: by Dutton, S. P., 1991, The University of Texas at Austin, Bureau of Economic Geology, topical report no. GRI-91/0057 prepared for the Gas Research Institute under contract no. 5082-211-0708, 48 p.

This report presents preliminary data and conclusions about the relationship of diagenesis to permeability in Frontier sandstones. (A later, more complete synthesis is found in topical report GRI-92/0127.) Diagenetic history influences reservoir quality in low-permeability gas-bearing sandstones of the Upper Cretaceous Frontier Formation along the Moxa Arch in the Green River Basin, southwest Wyoming. Frontier Formation sandstones are litharenites and sublitharenites. Clean sandstones contain an average of 1.6 percent primary porosity and 4.4 percent secondary porosity. Calcite, quartz, mixed-layer illite-smectite (MLIS), and illite are the most abundant cements. The relative order of occurrence of diagenetic events was (1) mechanical compaction, (2) formation of illite and MLIS rims, (3) precipitation of quartz overgrowths, (4) calcite cementation, (5) generation of secondary porosity, and (6) intergranular pressure solution and stylolitization. Low permeability in Frontier sandstones is caused by (1) loss of porosity due to compaction, (2) occlusion of primary pores by cements, particularly calcite and quartz, and (3) lining of primary pores by fibrous illite and MLIS. Unstressed permeability to air averages 0.21 md in upper-shoreface, 0.14 md in fluvial channel-fill, and 0.08 md in lower-shoreface sandstones.

Analysis of hydraulic fracture azimuth and height: Staged Field Experiment No. 4: by Laubach, S. E., Fix, J., Kalik, A., Warpinski, N., and Hill, R., 1992, *in* Application of advanced technologies in tight gas sandstones—Frontier Formation, Chimney Butte field, Sublette County, Wyoming: CER Corporation, report no. GRI-92/0394 prepared for Gas Research Institute, p. 115–132.

Description and interpretation of natural fracture patterns in sandstones of the Frontier Formation along the Hogsback, southwestern Wyoming: by Lorenz, J. C., and Laubach, S. E., 1994, The University of Texas at Austin, Bureau of Economic Geology, topical report prepared for Gas Research Institute under contract no. 5089-211-2059, SAND94-0153, 89 p.

Other Formations

Regional geology of the low-permeability, gas-bearing Cleveland Formation, western Anadarko Basin, Texas Panhandle: lithologic and depositional facies, structure, and sequence stratigraphy: by Hentz, T. F., 1992, The University of Texas at Austin, Bureau of Economic Geology, topical report no. GRI-92/0459 prepared for the Gas Research Institute under contract no. 5082-211-0708, 135 p.

The Upper Pennsylvanian (lower Missourian) Cleveland Formation produces gas from low-permeability ("tight") sandstone reservoirs in the western Anadarko Basin of the northeastern Texas Panhandle. In this six-county region, these reservoirs had produced >412 Bcf of natural gas through December 31, 1989. Because of their typically low permeability, the Cleveland sandstones require acidizing and hydraulic fracture treatment to produce gas at economic rates.

This report summarizes findings on the regional geology, depositional setting, sequence stratigraphy, and petrology of the Cleveland Formation. Investigation of this sandstone involved drilling cooperative wells. The Cleveland Formation contains an estimated 38 Tcf of gas in place.

Geologic challenges and opportunities of the Cherokee Group play (Pennsylvanian): Anadarko Basin, Oklahoma: by Hentz, T. F., 1993, The University of Texas at Austin, Bureau of Economic Geology, topical report prepared for the Gas Research Institute under contract no. 5082-211-0708, 29 p.

This report has three objectives: (1) to summarize both the geologic characteristics of the Cherokee Group and its production highlights; (2) to summarize what current Cherokee producing companies perceive to be the primary geologic challenges they face in developing the Cherokee play; and (3) to suggest geologic strategies to help respond to these challenges. To increase the understanding and utilization of natural gas resources in the Cherokee Group of west-central Oklahoma and to help assess future geological and technological needs for efficient development of this resource, this report highlights current geological knowledge of the Cherokee play.

Review of the Rose Run Sandstone Play of Ohio: Geological Framework and Exploration/ Production Techniques, Challenges, and Opportunities: by Mark J. Burn, The University of Texas at Austin, Bureau of Economic Geology, topical report no. GRI-93/0333 prepared for the Gas Research Institute under contract no. 5082-211-0708, 14 p.

Geology of a stratigraphically complex natural gas play: Canyon sandstones, Val Verde Basin, southwest Texas: by Laubach, S. E., Clift, S. J., Hamlin, H. S., Dutton, S. P., Hentz, T. F., Baek, Hwanjo, and Marin, B. A., 1994, The University of Texas at Austin, Bureau of Economic Geology, topical report no. GRI-94/0167 prepared for the Gas Research Institute under contract no. 5082-211-0708, 135 p.

The primary objective of this report is increased understanding of a key complex gas reservoir system—the Canyon sandstones of the Val Verde Basin, Texas. A secondary objective is to describe new stratigraphic, diagenetic, and structural geologic tools that will be widely applicable to other geologically complex reservoirs. This study aims to develop a model of the Canyon's physical geologic framework, which is necessary to understand the distribution and reservoir behavior of the gas resource. Using this geologic framework, Canyon operators can target areas where new wells, recompletions, or additional analyses will be most beneficial, thus reducing risk and costs while increasing the success of their exploration and development programs. Such knowledge is also necessary for effective, efficient application of new technologies for resource extraction.

Canyon sandstones have yielded almost 2.2 trillion cubic feet (Tcf) of gas and—in existing wells—contain estimated additional reserves of 2 Tcf. Operator interest and activity are at an all-time high, and continued drilling will undoubtedly lead to significant reserve growth. Average recovery per completion is a modest 0.7 billion cubic ft (Bcf), but the range is broad (up to 5 Bcf/well), and average drilling density is still relatively low. Low well density and the geologic complexity in the play documented by our study and recognized by operators suggest that opportunities exist for increasing Canyon productivity by taking advantage of better understanding of reservoir attributes.

Geological heterogeneity is the main cause of low productivity from Canyon sandstones. Most Canyon reservoirs occur within a crosscutting mosaic of lenticular channel and lobe facies of submarine-fan depositional systems. In the pervasively gas-saturated Canyon trends, the challenge for geologists is to understand and predict the distribution of high-deliverability compartments within the reservoir mosaic. Our study shows that the occurrence and nature of Canyon sweet spots are controlled by (1) depositional processes that control sandstone distribution and initial reservoir properties, (2) post-depositional diagenetic modifications that preserve or destroy reservoir quality, and (3) structural activity leading to the development of natural fractures and permeable pathways.

Regional domains of the Wilcox Lobo natural gas trend, South Texas: by Dickerson, P. W., Hamlin, H. S., Hentz, T. F., and Laubach, S. E., The University of Texas at Austin, Bureau of Economic Geology, topical report no. GRI 95/0027 prepared for the Gas Research Institute under contract no. 5082-211-0708, 49 p.

To increase understanding and utilization of gas resources in the Wilcox Lobo play of South Texas, this report describes regional geologic domains within the play. Recognition of domains provides a framework for subdividing the play, documenting and comparing reservoir properties, and predicting sandstone and reservoir compartment geometry and compositional patterns that have a bearing on reservoir quality.

This report is based on regional structural, stratigraphic, diagenetic, and production-pattern studies, information obtained from Railroad Commission of Texas files, and consultations with Wilcox Lobo operators. The Wilcox Lobo trend of Webb and Zapata Counties in South Texas contains the most prolific tight gas sandstones in the Texas Gulf Coast, yet it is also one of the most geologically complex. To date, published Lobo accounts have only partly answered important questions regarding depositional and structural framework, controls on production, and engineering characteristics of the play.

The Wilcox Lobo trend is the major low-permeability natural gas producer of the Texas Gulf Coast, having yielded almost 4 Tcf of gas. In recent years Lobo sandstones have accounted for a significant part of domestic tight-gas production: about 13 percent in 1991, the last year for which figures are available. Development activities are growing, marked by rising production rates, producing wells, and active rigs. The Lobo play is recognized to be among the most structurally complex plays in the Gulf Basin. As a result of submarine slumping and widespread normal faulting, sandstone correlation is hampered, nearly completely obscuring play-wide sandstone patterns. Consequently, although success rates are high, in part owing to deployment of 3-D seismic methods, operators surveyed in this study recognize opportunities for further increases in success rates and cost reductions if regional sandstone patterns and other regional geologic variables could be diagnosed.

Geology of the Davis Sandstone: by Collins, E. W., Laubach, S. E., and Dutton, S. P., 1992, *in* Investigation of the Davis Sandstone (Fort Worth Basin, Texas) as a suitable formation for the GRI hydraulic fracture test site: CER Corporation, topical report no. GRI-92/0194 prepared for the Gas Research Institute under contract no. 5091-211-2130, p. 4–12.

Reservoir Survey Reports

Geologic analysis of primary and secondary tight gas sand objectives, phase A—selective investigation of six stratigraphic units; phase B—initial studies: by Finley, R. J., Garrett, C. M., Jr., Han, J. H., Lin, Z. S., Seni, S. J., Saucier, A. E., and Tyler, Noel, 1983, The University of Texas at Austin, Bureau of Economic Geology, annual report no. GRI-84/0026 prepared for the Gas Research Institute under contract no. 5082-211-0708, 334 p.

The objective was to expand and verify interpretation of the depositional systems and other geologic and engineering characteristics of six blanket-geometry tight gas sandstones, to recommend two formations for research emphasis, and to begin initial geologic framework studies of these two formations. After investigating the geology and engineering characteristics of >30 blanket-geometry tight gas sandstones in a survey of 16 sedimentary basins, defining clastic depositional systems and using constituent facies as a method of evaluating the common features of stratigraphic units of different ages in diverse sedimentary and structural settings were emphasized. Blanket-geometry tight gas sandstones considered suitable for future research by the Gas Research Institute were found primarily within deltaic and barrier-strandplain depositional systems. Expected transferability of research results (extrapolation potential) between stratigraphic units was assessed, and more detailed study of six formations was recommended.

Of the six formations, the Frontier and the upper Almond Formations of the Greater Green River Basin, the Olmos Formation of the Maverick Basin, and the Mancos "B" Sandstone of the Piceance Basin were not recommended for further research at that time but should be researched to test barrier, offshore bar, and deltaic facies. The Corcoran and Cozzette Sandstones of the Piceance Creek Basin and the Travis Peak Formation of the East Texas Basin and North Louisiana Salt Basin were recommended for further research, and initial studies indicate that the Corcoran and Cozzette represent a barrier-strandplain system and contain barrier, offshore bar, and associated marginal-marine facies. Detailed studies of the Corcoran–Cozzette in Shire Gulch and Plateau fields show shoreface sequences common to the lower parts of both units and bay-lagoon and deltaic facies occurring in the upper parts. The Travis Peak Formation represents a deltaic system, having a lower subdivision of progradational deltaic facies, a thick middle subdivision of braided alluvial deposits, and an upper subdivision of marginal marine deposits influenced by marine transgression. Sandstones >50 ft thick are prominent in the middle subdivision in areas on the west flank of the Sabine Uplift. The estimated gas resources associated with the Corcoran–Cozzette and the Travis Peak in Texas are 3.7 and 17.3 Tcf, respectively.

Base maps and a selected number of well logs were acquired to prepare new cross sections and maps illustrating the stratigraphic characteristics of the Corcoran–Cozzette and Travis Peak Formations. Depositional systems and constituent facies were defined from cross sections and maps in conjunction with published and unpublished information compiled earlier. No major differences were noted between results reported here and the previous GRI data compilation, but a better understanding of the genetic stratigraphy of each unit was gained. For formations included in previous studies of tight gas resources, new resource estimates for particular formations were made by separating published data that had been combined for multiple formations. A completely new resource estimate was prepared for the Travis Peak Formation. Opportunities for cooperative coring and logging with operators were evaluated within the Corcoran–Cozzette producing trend. Within the East Texas Basin, study of a six-county area of high operator activity was emphasized.

Site Selection for GRI cooperative tight gas field research, volume II: geologic characteristics of selected low-permeability gas sandstones: by Baumgardner, R. W., Jr., Tye, R. S., Laubach, S. E., Diggs, T. N., Herrington, K. L., and Dutton, S. P., 1988, The University of Texas at Austin, Bureau of Economic Geology, topical report no. GRI-88/0180 prepared for the Gas Research Institute under contract no. 5082-211-0708, 225 p.

Geologic, engineering, and economic data on selected formations were compiled to provide a basis for siting the fourth Staged Field Experiment (SFE) for the Tight Gas Sands Research Program. The geologic units chosen are the Abo, Cleveland, and Frontier Formations, and the Mesaverde Group. Extrapolation potential is good for all formations except the Cleveland, whose thin deltaic package has no good analogy in other low-permeability sandstones. The Abo and Frontier have the best potential for extrapolation to other low-permeability formations. Average thickness of reservoirs is ~250 ft in the Mesaverde and Abo, ~160 ft in the Frontier, and ~120 ft in the Cleveland. Deepest production depth varies from 4,750 ft (Abo) to 12,198 ft (Second Frontier sandstone). Estimated resource base ranges from 3 Tcf (Abo) to 86 Tcf (Mesaverde). Prestimulation production ranges from too small to measure (Cleveland, Frontier, and Mesaverde) to 314 Mcf/d (Frontier). Post-stimulation production ranges from 3 Mcf/d (Mesaverde) to 12,250 Mcf/d (Cleveland). Permeability ranges from <0.0001 md (Frontier) to 1.3 md (Frontier). Natural fractures have been shown to be significant locally in the Mesaverde, but their contribution to reservoir permeability in the other formations is not well documented.

Increasing development efficiency in low-permeability gas reservoirs: a synopsis of Tight Gas Sands Project research: by Laubach, S. E., 1993, The University of Texas at Austin, Bureau of Economic Geology, topical report no. GRI–93/0045 prepared for the Gas Research Institute under contract no. 5082-211-0708, 71 p.

To enhance the application of research results by industry, this report provides a guide to the literature developed at the Bureau of Economic Geology in the Geological Analysis of Primary and Secondary Tight Gas Sands Objectives Project as part of the Gas Research Institute (GRI) Tight Gas Sands Research Program in the period 1982–1992.

Using diagenesis information to augment fracture analysis: by Laubach, S. E., Hentz, T. F., Johns, M. K., Baek, Hwanjo, and Clift, S. J., 1995, The University of Texas at Austin, Bureau of Economic Geology, topical report no. GRI–94/0455 prepared for Gas Research Institute under contract no. 5082-211-0708, 189 p.

The primary objective of this report is to obtain increased understanding of key reservoir elements—natural fractures—that exist in low-matrix-permeability natural gas reservoir sandstones. The study aims to describe relationships between natural fractures and diagenesis that can be used to help identify natural fracture-prone beds, controls on residual fracture porosity, and methods to infer fracture strike. Practical indirect methods to measure the likelihood of open fracture porosity and to map fracture strike are key results.

To efficiently and fully develop geologically complex natural gas reservoirs, attributes of natural fractures must be better understood than has hitherto been the case. Among other effects, natural fractures can enhance or inhibit formation permeability and affect success of well stimulation. Increasingly, natural fractures are viewed as targets for technologically advanced directional drilling. Natural fractures are widespread in subsurface sandstones, yet they are commonly an unknown quantity in formation evaluation and reservoir modeling because fractures typically do not intersect the wellbore where they can be detected and characterized. Methods are needed to provide information on key fracture-system properties such as fracture porosity and orientation and the location of fracture-prone areas or beds. These methods must overcome inherent and unavoidable sampling bias.

A better understanding of the relationship between fracturing and diagenesis can enhance prediction or diagnosis of fracture attributes. Diagenesis is the process involving physical and chemical changes in sediment after deposition that converts it to consolidated rock. In sandstones, diagenesis involves compaction, cementation, recrystallization, dissolution, and replacement of grains and cements. Because diagenetic changes occur under circumstances of tectonic and burial loading and fluid flow, fracture on a range of scales can also be an integral part of diagenesis. Diagenetic information can be obtained from proven petrographic approaches applied to full-diameter or sidewall core and, with calibration, from geophysical well-logging devices. Recognition of genetic links between diagenesis and fracture is the basis for seeking to identify diagenetic features that can be used to infer important correlated fracture attributes.

The aim of this study was to describe fracture and diagenetic relations in four low-matrix-permeability sandstone natural gas formations and to use that information to learn how diagenetic information can be applied to better predict fracture attributes. Three fracture-characterization issues were identified as being critical to effective reservoir development and modeling. These are recognition of fractured and fracture-prone layers, identification of controls on fracture porosity, and evaluation of fracture strike.

Atlas of Major Low-Permeability Sandstone Gas Reservoirs in the Continental United States: by Dutton, S. P., Clift, S. J., Hamilton, D. S., Hamlin, H. S., Hentz, T. F., Howard, W. E., Akhter, M. S., and Laubach, S. E., 1993, The University of Texas at Austin, Bureau of Economic Geology, topical report prepared for the Gas Research Institute under contract no. 5082-211-0708.

This report reviews 24 formations that, either because of the large volumes of natural gas reserves contained within them, or because of the data available for their characterization, are the most important tight gas sandstones in the United States. Assessment of these sandstone reservoirs indicates that geological controls play a critical role in gas producibility and that these reservoirs share a number of key geological attributes. Most of the tight gas reservoirs in this atlas are not mineralogically immature, muddy sandstones with large volumes of diagenetically reactive detrital clay matrix, but rather are clean sandstones deposited in high energy depositional settings whose intergranular pores have been largely occluded by authigenic cements (mainly quartz and calcite).

Reservoir genesis in tight gas reservoirs, just as in conventional oil and gas fields, clearly influences gas accumulation and recovery. The major tight gas sandstone reservoirs surveyed herein were deposited most commonly in barrier/strandplain (10) and deltaic (8) depositional systems. Fluvial (2), shelf (2), slope and basin (2), and fan-delta (1) depositional systems make up the remainder. Depositional systems govern the physical processes under which sediment is deposited and thus influence sediment sorting, packing, and separation of fines, and these parameters determine the original porosity and permeability. However, production characteristics of low-permeability gas reservoirs are in large part controlled by the diagenesis that the sediment has undergone after deposition.

Sediment composition, depth of burial, and age of the reservoir are important parameters that affect diagenetic alteration. Quartz is the most abundant cement in low-permeability sandstones; it occludes intergranular pores and thus has a strong effect on reducing permeability. Quartz cement volume in most formations increases with increasing burial depth. Calcite cement can also fill intergranular pores, but its distribution is not as uniform as quartz. Therefore, although calcite cement may destroy porosity and permeability in some beds or layers, its effect on permeability of a formation is not as widespread as that of quartz cement. Clay minerals occur in most low-permeability sandstones, and they lower permeability the most where they occur in intergranular pores. Because of their high surface-to-volume ratio, clays increase water saturation, which decreases relative permeability to gas.

Our survey shows that natural fractures are widespread features of tight gas sandstones. Because they are commonly vertical extension fractures that are easily missed by vertical core, detailed information on natural fracture attributes is rarely available. Fractures can enhance production, and in some formations they need to be taken into account in drilling, completion, and stimulation design.

The low-permeability formations covered in this volume have produced 22.3 Tcf of gas through 1988, and this figure does not include production from the "Clinton"-Medina and Berea Sandstones in the Appalachian Basin or the Davis Sandstone in the Fort Worth Basin. Estimated ultimate recovery from existing wells in the 21 formations for which production data are available is 47.1 Tcf.

BEG Publications and Other Monographs Listed Alphabetically by Author

Landsat-based lineament analysis, East Texas Basin and Sabine Uplift Area: by Baumgardner, R. W., Jr., 1987, The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 167, 26 p.

Diagenesis and burial history of the Lower Cretaceous Travis Peak Formation, East Texas: by Dutton, S. P., 1987, The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 164, 58 p.

Major low-permeability-sandstone gas reservoirs in the continental United States: by Dutton, S. P., Clift, S. J., Hamilton, D. S., Hamlin, H. S., Hentz, T. F., Howard, W. E., Akhter, M. S., and Laubach, S. E., 1993, The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 211, 221 p.

Geologic controls on reservoir properties of low-permeability sandstone, Frontier Formation, Moxa Arch, southwestern Wyoming: by Dutton, S. P., Hamlin, H. S., and Laubach, S. E., 1995, The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 234, 89 p.

Geologic characterization of low-permeability gas reservoirs, Travis Peak Formation, East Texas: by Dutton, S. P., Laubach, S. E., Tye, R. S., Baumgardner, R. W., Jr., and Herrington, K. L., 1991, The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 204, 89 p.

Geology and engineering characteristics of selected low-permeability gas sandstones: a national survey: by Finley, R. J., 1984, The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 138, 220 p.

Canyon sandstones—a geologically complex natural gas play in slope and basin facies, Val Verde Basin, southwest Texas: by Hamlin, H. S., Clift, S. J., Dutton, S. P., Hentz, T. F., and Laubach, S. E., 1995, The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 232, 44 p.

Depositional, structural, and sequence framework of the gas-bearing Cleveland formation (Upper Pennsylvanian), western Anadarko Basin, Texas Panhandle: by Hentz, T. F., The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 213, 73 p.

Structural history and origin of the Sabine Arch, East Texas and Northwest Louisiana: by Jackson, M. L. W., and Laubach, S. E., 1991, The University of Texas at Austin, Bureau of Economic Geology Geological Circular 91-3, 47 p.

Fracture analysis of the Travis Peak Formation, western flank of the Sabine Arch, East Texas: by Laubach, S. E., 1989, The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 185, 55 p.

In Focus—Tight Gas Sands Publications Listed Alphabetically by Author

Diagenesis of the Travis Peak tight gas sandstone, East Texas: by Dutton, S. P., 1987, In Focus—Tight Gas Sands, v. 4, no. 2, p. 18–25.

Comprehensive geologic basin analysis: application of a generic research approach to several tight gas sandstone formations: by Dutton, S. P., and Laubach, S. E., 1993, In Focus—Tight Gas Sands, v. 9, no. 1, p. 1–33.

Results of applied research in the Canyon sands, Val Verde Basin, southwest Texas: by Hamlin, H. S., Miller, William, Peterson, Richard, and Wiltgen, Nick, 1992, In Focus—Tight Gas Sands, v. 8, no. 1, p. 1–32.

Results of research in the Cleveland Formation, Anadarko Basin, North Texas: by Hentz, T. F., Hill, R. E., Whitehead, William, 1992, In Focus—Tight Gas Sands, v. 8, no. 1, p. 33–49.

Identifying key reservoir elements in low-permeability sandstones: natural fractures in the Frontier Formation, southwestern Wyoming: by Laubach, S. E., 1992, In Focus—Tight Gas Sands, v. 8, no. 2, p. 3–11.

Advancements in hydraulic fracture azimuth research, Green River Basin, Wyoming: by Laubach, S. E., 1992, In Focus—Tight Gas Sands, v. 8, no. 2, p. 12–22.

Geological analyses of tight gas sandstones: Canyon Sandstone: by Laubach, S. E., and Hamlin, H. S., 1994, In Focus—Tight Gas Sands, v. 10, no. 1, p. 35–38.

The Travis Peak/Hosston Formation of East Texas and North Louisiana—a laboratory for tight gas technology development: by Saucier, A. E., and Finley, R. J., 1984, In Focus—Tight Gas Sands, v. 1, no. 1, p. 15–25.

Geologic analysis of the Travis Peak tight gas sandstones: by Tye, R. S., Dutton, S. P., Laubach, S. E., and Finley, R. J., 1989, In Focus—Tight Gas Sands, v. 6, no. 1, p. 63–69.

Journal Publications Listed Alphabetically by Author

Bureau of Economic Geology: tight gas reservoir research: by Dutton, S. P., 1987, Texas Energy Reporter, v. 5, no. 2, p. 3–7.

Influence of provenance and burial history on diagenesis of Lower Cretaceous Frontier Formation sandstones, Green River Basin, Wyoming: by Dutton, S. P., 1993, Journal of Sedimentary Petrology, v. 63, no. 4, p. 665–677.

History of quartz cementation in the Lower Cretaceous Travis Peak Formation, East Texas: by Dutton, S. P., and Diggs, T. N., 1990, Journal of Sedimentary Petrology, v. 60, no. 2, p. 191–202.

Evolution of porosity and permeability in the Lower Cretaceous Travis Peak Formation, East Texas: by Dutton, S. P., and Diggs, T. N., 1992, American Association of Petroleum Geologists Bulletin, v. 76, no. 2, p. 252–269.

Controls on reservoir quality in tight sandstones of the Travis Peak Formation, East Texas: by Dutton, S. P., and Finley, R. J., 1988, SPE Formation Evaluation, v. 3, no. 1, p. 97–104.

Cementation and burial history of a low-permeability quartzarenite, Lower Cretaceous Travis Peak Formation, East Texas: by Dutton, S. P., and Land, L. S., 1988, Geological Society of America Bulletin, v. 100, no. 8, p. 1271–1282.

Developments in gas reservoir research with applications to tight sandstones: by Finley, R. J., 1985, Interstate Oil Compact Commission Committee Bulletin, v. 27, no. 1, p. 47–53.

An overview of selected blanket-geometry, low-permeability gas sandstones in Texas: by Finley, R. J., 1986, American Association of Petroleum Geologists Studies in Geology No. 24, p. 69–85.

Depositional systems and diagenesis of Travis Peak tight gas sandstone reservoirs, Sabine Uplift Area, Texas: by Fracasso, M. A., Dutton, S. P., and Finley, R. J., 1988, SPE Formation Evaluation, v. 3, no. 1, p. 105–115.

Sequence stratigraphy of the Upper Pennsylvanian Cleveland formation: a major tight-gas sandstone, western Anadarko Basin, Texas Panhandle: by Hentz, T. F., 1994, American Association of Petroleum Geologists Bulletin, v. 78, no. 4, p. 569–595.

Subsurface fractures and their relationship to stress history in East Texas basin sandstone: by Laubach, S. E., 1988, Tectonophysics, v. 156, p. 37–49.

Paleostress directions from the preferred orientation of closed microfractures (fluid-inclusion planes) in sandstone, East Texas basin, U.S.A.: by Laubach, S. E., 1989, Journal of Structural Geology, v. 11, no. 5, p. 603–611.

Fracture networks in selected Cretaceous sandstones of the Green River and San Juan Basins: by Laubach, S. E., 1992, *in* Schmoker, J. W., Coalson, E. B., and Brown, C. A., eds., Geological studies relevant to horizontal drilling in western North America: Rocky Mountain Association of Geologists, p. 61–74.

A method to detect natural fracture strike in sandstone: by Laubach, S. E., in press, AAPG Bulletin.

Origin of arches in the northwestern Gulf of Mexico basin: by Laubach, S. E., and Jackson, M. L. W., 1990, Geology, v. 18, no. 7, p. 595–598.

Natural fractures in Sonora Canyon sandstones, Sonora and Sawyer fields, Sutton County, Texas: by Marin, B. A., Clift, S. J., Hamlin, H. S., and Laubach, S. E., 1993, Society of Petroleum Engineers Paper No. SPE 25895, p. 523–531.

Fluvial-sandstone reservoirs of the Travis Peak Formation, East Texas Basin: Tye, R. S., 1991, in Miall, A. D., and Tyler, Noel, eds., The three-dimensional facies architecture of terrigenous clastic sediments and its implications for hydrocarbon discovery and recovery: SEPM (Society for Sedimentary Geology) Concepts in Sedimentology and Paleontology, v. 3, p. 172–188.

Conference Papers

Fracture toughness and crack morphology of a variably cemented sandstone: by Baek, Hwanjo, Laubach, S. E., and Nelson, P. P., 1994, Transactions, SEM (Society for Experimental Mechanics), p. 153–158. *Talk presented* by Hwanjo Baek at SEM Spring Conference and Exhibits, Baltimore, Maryland, 1994.

Depositional environments, petrology, and fractures of the Atoka Davis sandstone: a low-permeability gas-bearing sandstone of the Fort Worth Basin, North-Central Texas: by Collins, E. W., Laubach, S. E., Dutton, S. P., and Hill, R. E., 1992, Transactions, Southwest Section AAPG, Publication SWS 92-90, p. 221–230. *Abstract in* 1992 American Association of Petroleum Geologists Bulletin, v. 76, no. 4, p. 574. *Poster session presented* by E. W. Collins at annual meeting of Southwest Section AAPG in Midland, Texas, April 12–15, 1992.

Petrography and diagenesis of Lower Cretaceous Travis Peak (Hosston) Formation, East Texas: by Dutton, S. P., 1986, Gulf Coast Association of Geological Societies Transactions, v. 36, p. 73–81. *Abstract in* 1986 American Association of Petroleum Geologists Bulletin, v. 70, no. 9, p. 1180. *Paper presented* at annual meeting of Gulf Coast Association of Geological Societies in Baton Rouge, Louisiana, October 22–24, 1986.

Depositional and diagenetic controls on reservoir quality in tight sandstones of the Travis Peak (Hosston) Formation, East Texas: by Dutton, S. P., and Finley, R. J., 1986, Proceedings, 1986 Society of Petroleum Engineers/U.S. Department of Energy/Gas Research Institute Joint Symposium on Unconventional Gas Technology, Louisville, Kentucky, Paper SPE 15220, p. 153–162. *Talk presented* by S. P. Dutton at Joint Symposium on Unconventional Gas Technology in Louisville, Kentucky, May 18–21, 1986.

Organic geochemistry of the Lower Cretaceous Travis Peak Formation, East Texas Basin: by Dutton, S. P., Finley, R. J., and Herrington, K. L., 1987, Gulf Coast Association of Geological Societies Transactions, v. 37, p. 65–74. *Abstract in* 1987 American Association of Petroleum Geologists Bulletin, v. 71, no. 9, p. 1116. *Paper presented* by S. P. Dutton at 1987 annual meeting of Gulf Coast Association of Geological Societies in San Antonio, Texas, October 28–30, 1987.

Geologic controls on reservoir properties of Frontier Formation low-permeability gas reservoirs, Moxa Arch, Wyoming: Dutton, S. P., and Hamlin, H. S., 1991, Proceedings, SPE Joint Rocky Mountain Regional/Low Permeability Reservoirs Symposium, Paper SPE 21851, p. 479–488. *Paper presented* by S. P. Dutton at Joint Symposium on Low Permeability Reservoirs in Denver, Colorado, April 14–17, 1991.

Interaction of burial history and diagenesis of the Upper Cretaceous Frontier Formation, Moxa Arch, Green River Basin, Wyoming: by Dutton, S. P., and Hamlin, H. S., 1992, Wyoming Geological Association Forty-Third Field Conference Guidebook, p. 37–50. *Abstract in* 1992 American Association of Petroleum Geologists Bulletin, v. 76, no. 8, p. 1258. *Talk presented* by S. P. Dutton at annual meeting of Rocky Mountain Section AAPG in Casper, Wyoming, September 13–16, 1992.

Depositional, diagenetic, and structural controls on reservoir properties of low-permeability sandstone, Travis Peak Formation, East Texas: by Dutton, S. P., Laubach, S. E., and Tye, R. S., 1991, Gulf Coast Association of Geological Societies Transactions, v. 41, p. 209–220. *Abstract in* 1991 American Association of Petroleum Geologists Bulletin, v. 75, no. 9, p. 1521. *Talk presented* by S. P. Dutton at annual meeting of Gulf Coast Association of Geological Societies AAPG in Houston, Texas, October 16–18, 1991.

Reservoir properties and gas productivity of the Corcoran and Cozzette tight sandstones, Colorado: by Finley, R. J., 1985, Proceedings, 1985 Society of Petroleum Engineers/Department of Energy Joint Symposium on Low Permeability Reservoirs, Denver, Colorado, Paper SPE/DOE 13852, p. 33–45. *Talk presented* at Joint Symposium on Low Permeability Reservoirs in Denver, Colorado, May 19–22, 1985.

Subregional stratigraphic relations, diagenesis, and reservoir quality of Travis Peak tight gas sandstones, Sabine Uplift area, Texas: by Fracasso, M. A., Finley, R. J., and Dutton, S. P., 1986, Society of Petroleum Engineers, East Texas regional meeting, Paper SPE 14666, p. 133–142. *Talk presented* by M. A. Fracasso at Society of Petroleum Engineers East Texas regional meeting in Tyler, Texas, April 20–22, 1986.

Stratigraphy and diagenesis of Sonora Canyon deep-water sandstones, Val Verde Basin, southwest Texas: by Hamlin, H. S., Clift, S. J., and Dutton, S. P., 1992, Transactions, Southwest Section AAPG, Publication SWS 92-90, p. 209–220. *Abstract in* 1992 American Association of Petroleum Geologists Bulletin, v. 76, no. 4, p. 575–576. *Talk presented* by H. S. Hamlin at annual meeting of Southwest Section AAPG in Midland, Texas, April 12–15, 1992.

Reservoir characterization of the Frontier tight gas sand, Green River Basin, Wyoming: by Harrison, C. W., III, and Dutton, S. P., 1991, Proceedings, Joint SPE Rocky Mountain Regional/ Low Permeability Reservoirs Symposium, Paper SPE 21879, p. 717–725. *Paper presented* by C. W. Harrison at Joint Symposium on Low Permeability Reservoirs in Denver, Colorado, April 14–17, 1991.

Diagenesis of Ozona Canyon fracture fills: implications for potential fractured reservoirs in the Ozona gas play, Val Verde Basin, West Texas: by Hentz, T. F., 1995, West Texas Geological Society, Publication 95–98, p. 69–81. *Talk presented* at West Texas Geological Society Fall Symposium in Midland, Texas, November 2–3, 1995.

Low-permeability, gas-bearing Cleveland Formation (Upper Pennsylvanian), western Anadarko Basin: structure, paleoenvironments, and paleotectonic control on depositional patterns: by Hentz, T. F., 1992, Transactions, Southwest Section American Association of Petroleum Geologists, Publication SWS 92-90, p. 231–252. *Talk presented* at Southwest Section, AAPG meeting, 1992.

Cretaceous and Tertiary compressional tectonics as the cause of the Sabine Arch, East Texas and northwest Louisiana: by Jackson, M. L. W., and Laubach, S. E., 1988, Transactions, Gulf Coast Association of Geological Societies, v. 38, p. 245–256. *Abstract in* 1987 American Association of Petroleum Geologists Bulletin, v. 72, no. 9, p. 1114. *Paper presented* by S. E. Laubach at 1988 annual meeting of Gulf Coast Association of Geological Societies in New Orleans, October 19–21, 1988.

Fracture patterns in low-permeability-sandstone gas reservoir rocks in the Rocky Mountain region: by Laubach, S. E., 1991, Proceedings, SPE Joint Rocky Mountain Regional/Low Permeability Reservoirs Symposium, Paper SPE 21853, p. 501–510. *Paper presented* by S. E. Laubach at Joint Symposium on Low Permeability Reservoirs in Denver, Colorado, April 14–17, 1991.

Fracture studies of sandstone, chalk, and coal: by Laubach, S. E., 1991, *in* Arya, F. R., moderator, Short course notes: identifying and interpreting fractures: Houston Geological Society, p. 6-1–6-30. *Paper presented* by S. E. Laubach at Gulf Coast Association of Geological Societies Transactions meeting in Houston, 1991.

Fracture detection in low-permeability reservoir sandstone: a comparison of BHTV and FMS logs to core: by Laubach, S. E., Baumgardner, R. W., Jr., Monson, E. R., Hunt, E., and Meador, K. A., 1988, Proceedings, 1988 Society of Petroleum Engineers Annual Technical Conference, Paper SPE 18119, p. 129–139. *Talk presented* by S. E. Laubach at 1988 SPE Annual Technical Conference in Houston, October 2–5, 1988. *Talk also presented* by invitation at AAPG annual meeting in San Antonio, Texas, April 23–26, 1989, *and at* SPE Fractured Reservoirs Forum, Crested Butte, Colorado, July 1989.

Stress directions in Cretaceous Frontier Formation, Green River Basin, Wyoming: by Laubach, S. E., Clift, S. J., Hill, R. E., and Fix, J. E., 1992, Wyoming Geological Association Forty-Third Field Conference Guidebook, p. 75–86.

Strength anisotropy in low-permeability sandstone gas reservoir rocks: application of the axial point-load test: by Clift, S. J., Laubach, S. E., and Holder, J., 1992, Transactions, Gulf Coast Association of Geological Societies, v. 42, p. 61–72. *Paper presented* by S. E. Laubach at GCAGS meeting in Jackson, Mississippi, 1992.

Fractures in Frontier Formation: by Laubach, S. E., Hamlin, H. S., and Lorenz, J. C., 1992, Road log and geologic description of field trip stops, southwest Wyoming: Wyoming Geological Association Forty-Third Field Conference Roadlog volume, p. 105–112.

Preliminary assessment of natural fracture patterns in Frontier Formation sandstones, southwestern Wyoming: by Laubach, S. E., and Lorenz, J. C., 1992, Wyoming Geological Association Forty-Third Field Conference Guidebook, p. 87–96. *Abstract in* 1992 American Association of Petroleum Geologists Bulletin, v. 76, no. 8, p. 1262. *Talk presented* by S. E. Laubach at annual meeting of Rocky Mountain Section AAPG in Casper, Wyoming, September 13–16, 1992.

Coring-induced fractures: indicators of hydraulic fracture propagation in a naturally fractured reservoir: by Laubach, S. E., and Monson, E. R., 1988, Proceedings, 1988 Society of Petroleum Engineers Annual Technical Conference, Houston, Texas, Paper SPE 18164, p. 587–596. *Paper presented* by S. E. Laubach at 1988 SPE Annual Technical Conference in Houston, October 2–5, 1988.

Reservoir engineering properties and production characteristics of selected tight gas fields, Travis Peak Formation, East Texas Basin: by Lin, Z. S., and Finley, R. J., 1985, Proceedings, 1985 Society of Petroleum Engineers/Department of Energy Joint Symposium on Low Permeability Reservoirs, Denver, Colorado, Paper SPE/DOE 13901, p. 509–522. *Paper presented* by Z. S. Lin at Joint Symposium on Low Permeability Reservoirs in Denver, Colorado, May 19–22, 1985.

Effect of extraction and drying on flow, capillary, and electrical properties of Travis Peak cores containing fibrous illite: by Luffel, D. L., Herrington, K. L., and Walls, J. D., 1990, Proceedings, 1990 Society of Petroleum Engineers Annual Technical Conference, Paper SPE 20725, p. 131–138. *Talk presented* by D. L. Luffel at 1990 SPE Annual Technical Conference in New Orleans, September 1990.

Fibrous illite controls productivity in Frontier gas sands, Moxa Arch, Wyoming: by Luffel, D. L., Herrington, K. L., and Harrison, C. W., 1991, Proceedings, SPE Joint Rocky Mountain Regional/ Low Permeability Reservoirs Symposium, Denver, Colorado, Paper SPE 21876, p. 695–704. *Paper presented* by D. L. Luffel at Joint Symposium on

Low Permeability Reservoirs in Denver, Colorado, April 14–17, 1991.

Natural fractures in Sonora Canyon sandstones, Sonora and Sawyer fields, Sutton County, Texas: by Marin, B. A., Clift, S. J., Hamlin, H. S., and Laubach, S. E., 1993, Proceedings, SPE Joint Rocky Mountain Regional/Low Permeability Reservoirs Symposium, Denver, Colorado, Paper SPE 25895. *Paper presented* by S. E. Laubach at Joint Symposium on Low Permeability Reservoirs in Denver, Colorado, April 26–28, 1993.

The Travis Peak (Hosston) Formation of East Texas and North Louisiana: by Saucier, A. E., Finley, R. J., and Dutton, S. P., 1985, Proceedings, 1985 Society of Petroleum Engineers/Department of Energy Joint Symposium on Low Permeability Reservoirs, Denver, Colorado, Paper SPE/DOE 13850, p. 15–22. *Paper presented* by S. P. Dutton at Joint Symposium on Low Permeability Reservoirs in Denver, Colorado, May 19–22, 1985.

The role of geology in characterizing low-permeability sandstones, North Appleby field, East Texas Basin: by Tye, R. S., Laubach, S. E., Dutton, S. P., and Herrington, K. L., 1989, Proceedings, Society of Petroleum Engineers 1989 Joint Rocky Mountain Regional Meeting and Low-Permeability Reservoir Symposium, Denver, Colorado, Paper SPE 18964, p. 355–365. *Paper presented* by R. S. Tye at 1989 Joint Rocky Mountain Regional Meeting and Low Permeability Reservoir Symposium, Denver, Colorado, March 5–7, 1989.

In situ stresses: a comparison between log-derived values and actual field-measured values in the Travis Peak Formation of East Texas: by Whitehead, W. S., Hunt, E. R., Finley, R. J., and Holditch, S. A., 1986, Proceedings, 1986 Society of Petroleum Engineers DOE/GRI Joint Symposium on Unconventional Gas Technology, Louisville, Kentucky, Paper SPE 15209, p. 19–34.

Conference Proceedings Publications

Analysis of subsurface structure via lineament study, East Texas and northwest Louisiana (abs.): by Baumgardner, R. W., Jr., 1986, Geological Society of America, Abstracts with Programs, v. 18, no. 6, p. 536. *Talk presented* at annual meeting of Geological Society of America in San Antonio, Texas, November 10–13, 1986.

Wellbore ellipticity in East Texas: in situ stress or fracture-related spalling? (abs.): by Baumgardner, R. W., Jr., and Laubach, S. E., 1987, Eos, Transactions of the American Geophysical Union, v. 68, no. 44, p. 1460. *Talk presented* by R. W. Baumgardner, Jr., at annual fall meeting of American Geophysical Union in San Francisco, California, December 7–11, 1987.

Stratigraphic analysis of fluvial and marine sandstone with borehole-imaging geophysical logs and core (abs.): by Buehring, R., Laubach, S. E., and Hamlin, H. S., 1990, Geological Society of America Abstracts with Programs, v. 22, no. 7, p. A47. *Poster presented* by S. E. Laubach and R. W. Buehring at annual meeting of Geological Society of America in Dallas, Texas, November 10–13, 1990.

Pore characterization by scanning electron microscope of low-permeability gas sandstones, Travis Peak Formation, East Texas (abs.): by Dutton, S. P., 1986, American Association of Petroleum Geologists Bulletin, v. 70, no. 5, p. 585. *Talk presented* at annual meeting of American Association of Petroleum Geologists in Atlanta, Georgia, June 15–18, 1986.

Diagenesis and burial history of Lower Cretaceous Travis Peak sandstone, East Texas (abs.): by Dutton, S. P., 1987, American Association of Petroleum Geologists Bulletin, v. 71, no. 5, p. 551. *Talk presented* at annual meeting of American Association of Petroleum Geologists in Los Angeles, California, June 7–10, 1987.

Regional diagenetic studies: an approach to paleohydrology and basin evolution (abs.): by Dutton, S. P., 1988, Colorado School of Mines, Workshop on Quantitative Dynamic Stratigraphy (QDS), p. 5–6. *Talk presented* at Workshop on Quantitative Dynamic Stratigraphy in Deckers, Colorado, February 14–18, 1988.

Variations in diagenesis and reservoir quality in the Frontier Formation along the Moxa Arch, Green River Basin, Wyoming (abs.): by Dutton, S. P., 1990, American Association of Petroleum Geologists Bulletin, v. 74, no. 8, p. 1321–1322. *Talk presented* at Rocky Mountain Section AAPG Annual Meeting in Denver, Colorado, September 16–19, 1990.

Late-stage diagenesis and development of secondary porosity in Frontier Formation low-permeability sandstones, Green River Basin, Wyoming, USA (abs.): by Dutton, S. P., 1992, American Association of Petroleum Geologists 1992 Annual Convention Official Program, p. 34. *Talk presented* at AAPG Annual Meeting in Calgary, Canada, June 21–24, 1992.

Porosity preservation by early siderite cementation in Sonora Canyon sandstones, Val Verde Basin, southwest Texas (abs.): by Dutton, S. P., Clift, S. J., Folk, R. L., Hamlin, H. S., and Marin, B. A., 1993, American Association of Petroleum Geologists 1993 Annual Convention Official Program, p. 95. *Talk presented* at AAPG Annual Meeting in New Orleans, Louisiana, April 25–28, 1993.

Stratigraphic and depth variations in authigenic cement distribution, Lower Cretaceous Travis Peak Formation, East Texas (abs.): by Dutton, S. P., and Diggs, T. N., 1988, Geological Society of America, Abstracts with Programs, v. 20, no. 7, p. A375. *Talk presented* by S. P. Dutton at GSA Annual Meeting in Denver, Colorado, October 31–November 3, 1988.

Controls on permeability distribution in Lower Cretaceous Travis Peak Formation, East Texas (abs.): by Dutton, S. P., and Diggs, T. N., 1989, American Association of Petroleum Geologists Bulletin, v. 73, no. 3, p. 352. *Talk presented* by S. P. Dutton at annual meeting of American Association of Petroleum Geologists in San Antonio, Texas, April 23–26, 1989.

Geology of major low-permeability sandstone gas reservoirs in the continental United States (abs.): by Dutton, S. P., and Laubach, S. E., 1993, Geological Society of America, Abstracts with Programs, v. 25, no. 6, p. A-300. *Talk presented* by S. P. Dutton at annual meeting of Geological Society of America in Boston, Massachusetts, October 25–28, 1993.

Comparison of depositional systems and reservoir characteristics of selected blanket-geometry tight gas sandstones (abs.): by Finley, R. J., 1984, American Association of Petroleum Geologists Bulletin, v. 67, no. 3, p. 460–461. *Talk presented* by R. J. Finley at annual meeting of American Association of Petroleum Geologists in Dallas, Texas, April 17–20, 1983.

Geology and reservoir characteristics of tight gas sandstones in the Travis Peak Formation, Chapel Hill field, East Texas (abs.): by Finley, R. J., and Dutton, S. P., 1987, American Association of Petroleum Geologists Bulletin, v. 71, no. 5, p. 556. *Talk presented* by R. J. Finley at 1987 annual meeting of American Association of Petroleum Geologists in Los Angeles, California, June 7–10, 1987.

Depositional systems of a tight gas-productive barrier-strandplain sequence: Corcoran and Cozzette Sandstones, northwest Colorado (abs.): by Finley, R. J., and Ladwig, L. R., 1985, American Association of Petroleum Geologists Bulletin, v. 69, no. 2, p. 255. *Talk presented* by R. J. Finley at annual meeting of the American Association of Petroleum Geologists in New Orleans, Louisiana, March 24–27, 1985.

Depositional systems and productive characteristics of major low-permeability gas sandstones in Texas (abs.): by Finley, R. J., Seni, S. J., Tyler, Noel, and Lin, Z. S., 1984, American Association of Petroleum Geologists Bulletin, v. 68, no. 4, p. 476. *Talk presented* by R. J. Finley at annual meeting of American Association of Petroleum Geologists in San Antonio, Texas, May 20–23, 1984.

Geology of natural gas reservoir: upper Travis Peak Formation, western flank of Sabine Uplift, East Texas (abs.): by Fracasso, M. A., 1986, American Association of Petroleum Geologists Bulletin, v. 70, no. 5, p. 591. *Talk presented* at annual meeting of American Association of Petroleum Geologists in Atlanta, Georgia, June 15–18, 1986.

Fluvio-deltaic deposition of reservoir sandstones in the upper Travis Peak Formation (Lower Cretaceous), Waskom field, East Texas Basin (abs.): by Fracasso, M. A., 1987, Society of Economic Paleontologists and Mineralogists, Annual Midyear Meeting, Abstracts Volume IV, p. 27–28. *Talk presented* at annual midyear meeting of the Society of Economic Paleontologists and Mineralogists in Austin, Texas, August 20–23, 1987.

Facies-related permeability trends in the Frontier Formation along the Moxa Arch, Green River Basin, Wyoming (abs.): by Hamlin, H. S., and Buehring, R. L., 1990, American Association of Petroleum Geologists Bulletin, v. 74, no. 8, p. 1325. *Poster session presented* by H. S. Hamlin at Rocky Mountain Section AAPG Annual Meeting in Denver, Colorado, September 16–19, 1990.

Geologically complex gas reservoirs in slope and basin facies, Canyon sandstones, Val Verde Basin, southwest Texas (abs.): by Hamlin, H. S., Clift, S. J., Dutton, S. P., Hentz, T. F., and Laubach, S. E., 1994, Houston Geological Society Bulletin, v. 37, no. 1, p. 11. *Oral presentation given* to Houston Geological Society in Houston, Texas.

Paleotectonic controls on sandstone trends and depositional facies distribution of the low-

permeability, gas-bearing Cleveland formation (Upper Pennsylvanian), Texas Panhandle (abs.): by Hentz, T. F., 1992, American Association of Petroleum Geologists Bulletin, v. 76, no. 4, p. 576. *Oral presentation given* to annual meeting of Southwest Section of the American Association of Petroleum Geologists in Midland, Texas, April 21–24, 1992.

Reservoir framework and exploration potential of the Cleveland formation (western Anadarko Basin) using a sequence-stratigraphic model (abs.): by Hentz, T. F., 1993, American Association of Petroleum Geologists Bulletin, v. 77, no. 9, p. 1573–1574. *Oral presentation given* to annual meeting of Mid-Continent Section of the American Association of Petroleum Geologists in Amarillo, Texas, October 10–12, 1993.

Sequence-stratigraphic context of Pennsylvanian (Desmoinesian-Missourian) siliciclastics: Cleveland formation and Marmaton Group, western Anadarko Basin, Texas Panhandle (abs.): by Hentz, T. F., 1993, Geological Society of America, South-Central Section, Abstracts with Programs, v. 25, no. 1, p. 13. *Oral presentation given* to annual meeting of South-Central Section of the Geological Society of America in Fort Worth, Texas, March 14–16, 1993.

Sequence stratigraphy of coastal plain to shelf-slope facies tracts: Middle to Upper Pennsylvanian Cleveland and Marmaton siliciclastics, western Anadarko Basin, Texas Panhandle (abs.): by Hentz, T. F., 1993, American Association of Petroleum Geologists 1993 Annual Convention Program, p. 117. *Poster session presented* at annual meeting of American Association of Petroleum Geologists in New Orleans, Louisiana, April 25–28, 1993.

Evidence for Sevier and Laramide deformation in the Gulf of Mexico basin (abs.): by Jackson, M. L. W., and Laubach, S. E., 1987, Geological Society of America Abstracts with Programs, v. 19, no. 5, p. 285. *Poster session presented* at annual meeting of the Rocky Mountain Section of the Geological Society of America in Boulder, Colorado, May 2–4, 1987.

Mapping subsurface fracture trends (abs.): by Laubach, S. E., 1987, Eos, Transactions of the American Geophysical Union, v. 68, no. 16, p. 299. *Invited presentation* at annual spring meeting of the American Geophysical Union in Baltimore, Maryland, May 18–22, 1987, as part of a special session on Field Approaches and Measurement Techniques for Quantifying Spatial Variability in Porous Media.

Brittle microstructure of folded quartzite (abs.): by Laubach, S. E., 1988, Eos, Transactions of the American Geophysical Union, v. 69, no. 16, p. 472.

Origin of natural fractures in sandstone from a passive margin basin (abs.): by Laubach, S. E., 1988, Eos, Transactions of the American Geophysical Union, v. 69, no. 44, p. 1433. *Talk presented* at 1988 fall meeting of the American Geophysical Union, San Francisco, California, December 7, 1988. *Talk also presented* at conference "Deformation Mechanisms, Rheology, and Tectonics," The University, Leeds, England, March 27–30, 1989.

Significance of natural and coring-induced fractures in the Travis Peak Formation for reservoir stimulation (extended abs.): by Laubach, S. E., 1988, Transactions, Gulf Coast Association of Geological Societies, v. 38, p. 591. *Abstract also in* 1987 American Association of Petroleum Geologists Bulletin, v. 72, no. 9, p. 1115. *Paper presented* by S. E. Laubach at 1988 annual meeting of Gulf Coast Association of Geological Societies in New Orleans, October 19–21, 1988.

Fracture swarms in low-permeability-sandstone gas reservoir rocks in New Mexico, Colorado, and Wyoming: implications for exploration and development (abs.): by Laubach, S. E., 1991, American Association of Petroleum Geologists Bulletin, v. 75, no. 6, p. 1130–1131. *Talk presented* at Rocky Mountain Section AAPG Annual Meeting in Billings, Montana, July 28–31, 1991.

Multiple generations of fluid inclusions in Cretaceous quartz veins from the Gulf of Mexico basin (abs.): by Laubach, S. E., and Boardman, S., 1989, Geological Society of America, Abstracts with Programs, v. 21, no. 6, p. A64. *Talk presented* at Geological Society of America annual meeting, St. Louis, Missouri, 1989.

Using indentation (axial point-load) tests to evaluate strength anisotropy and stress directions in low-permeability gas reservoir sandstones (abs.): by Laubach, S. E., Clift, S. J., and Holder, J.,1992, American Association of Petroleum Geologists Bulletin, v. 76, no. 8, p. 1262. *Talk presented* by S. E. Laubach at annual meeting of Rocky Mountain Section AAPG in Casper, Wyoming, September 13–16, 1992.

Coevolution of fracture pattern, rock mechanical properties, and diagenesis in a low-permeability gas reservoir sandstone, East Texas (abs.): by Laubach, S. E., Hoak, T. E., Dutton, S. P., and Diggs,

T. N., 1989, Geological Society of America, Abstracts with Programs, v. 21, no. 1, p. 16. *Talk presented* by S. E. Laubach at Geological Society of America South-Central Section Annual Meeting in Arlington, Texas, March 12–14, 1989.

Opportunities for horizontal drilling in fractured low-permeability sandstones (abs.): by Laubach, S. E., and Marin, B. A., 1992, Proceedings, Horizontal Drilling Symposium, domestic and international case studies, Rocky Mountain Association of Geologists, Denver, Colorado, October 18–21, 1992, unpaginated. *Talk presented* at RMAG Horizontal Drilling Symposium, 1992.

Characteristics of subsurface natural fractures in East Texas (abs.): by Laubach, S. E., and Monson, Eric, 1987, Eos, Transactions of the American Geophysical Union, v. 68, no. 16, p. 428. *Talk presented* by S. E. Laubach at annual spring meeting of American Geophysical Union in Baltimore, Maryland, May 18–22, 1987.

Fracture-trace maps of upper Pictured Cliffs Sandstone pavements, San Juan Basin, Colorado (abs.): by Laubach, S. E., Tremain, C. M., Whitehead, N. H., III, and Baumgardner, R. W., Jr., 1990, Geological Society of America Abstracts with Programs, v. 22, no. 7, p. A202. *Talk presented* by S. E. Laubach at GSA national meeting, Dallas, Texas, 1990.

Fluvial sandstone reservoirs of the Travis Peak (Hosston) Formation, East Texas Basin (abs.): by Tye, R. S., 1989, American Association of Petroleum Geologists Bulletin, v. 73, no. 3, p. 421. *Talk presented* at AAPG annual meeting in San Antonio, Texas, April 23–26, 1989.

Oral Presentations—No Published Paper or Abstract Listed Alphabetically by Presenter

R. W. Baumgardner, Jr.

"Lineament analysis, a supplement to subsurface fracture studies: Landsat and radar study of East Texas and Midland Basin": presented to visiting geologists involved in a project to drill and fracture horizontal wells in tight gas sandstone, Bureau of Economic Geology, Austin, Texas, 1987.

"Lineament analysis, a supplement to subsurface fracture studies: Landsat and radar study of East Texas": presented to the Geographic Information Systems and Remote Sensing Symposium, Texas Natural Resources Information System, Austin, Texas, 1987.

S. J. Clift

"Advancements in sandstone analysis through axial point-load testing": presented to the Bureau of Economic Geology Seminar, Austin, Texas, 1992.

"Ozona Canyon Sandstones: Val Verde Basin": presented to the Bureau of Economic Geology Seminar, Austin, Texas, 1993.

S. P. Dutton

"Diagenesis of Travis Peak sandstones": presented to the Bureau of Economic Geology Seminar, Austin, Texas, 1985.

Core and poster display on Tight Gas Sandstone Project: presented to the Society of Petroleum Engineers, East Texas regional meeting, Tyler, Texas, 1986.

"Diagenesis and burial history of the Lower Cretaceous Travis Peak Formation, East Texas": presented to the Department of Geological Sciences, technical sessions, The University of Texas at Austin, 1986.

"Diagenesis and burial history of Travis Peak sandstones": presented to the Bureau of Economic Geology Seminar, Austin, Texas, 1986.

Results of GRI-sponsored sandstone diagenesis research presented to a delegation of scientists from the Beijing Graduate School, East China Petroleum Institute, Beijing, China PRC, at the Bureau of Economic Geology, Austin, Texas, 1986.

"Petrography and diagenesis of the Lower Cretaceous Travis Peak (Hosston) Formation, East Texas": presented to the East Texas Geological Society, Tyler, Texas, 1987.

"Petrography and diagenesis of the Lower Cretaceous Travis Peak (Hosston) Formation, East Texas": presented to Friends of the Mesozoic, Houston, Texas, 1987.

"Petrography and diagenesis of the Lower Cretaceous Travis Peak (Hosston) Formation, East Texas": presented to the Shreveport Geological Society, Shreveport, Louisiana, 1987.

"Control on permeability distribution in the Lower Cretaceous Travis Peak Formation, East Texas": presented to the Bureau of Economic Geology Seminar, Austin, Texas, 1988.

"Depositional and diagenetic controls on permeability distribution in the Lower Cretaceous Travis Peak Formation, East Texas": presented to the Department of Geological Sciences Soft Rock Seminar, The University of Texas at Austin, Austin, Texas, 1988.

"Diagenesis of the Travis Peak Formation, East Texas": presented to the Shell Oil Company Research Lab, Bellaire, Texas, 1988.

"Cementation and burial history of a low-permeability quartzarenite, Lower Cretaceous Travis Peak Formation, East Texas": presented to the Department of Geology, University of New Orleans, New Orleans, Louisiana, 1989.

"Depositional and diagenetic controls on permeability distribution in the Lower Cretaceous Travis Peak Formation, East Texas": presented to the Shreveport Chapter, Society of Professional Well Log Analysts, Shreveport, Louisiana, 1989.

"Diagenesis of Frontier tight gas sandstones": presented to the Bureau of Economic Geology Seminar, Austin, Texas, 1990.

"Integrated geological characterization of low-permeability ("tight gas") sandstone reservoirs": presented to the Forum on Improved Oil & Gas Recovery sponsored by TIPRO and the Bureau of Economic Geology, Amarillo, Texas, 1991.

"Natural gas reserves, supply, and demand: an assessment of the natural gas resource base of the United States": presented to the Commercial and Industrial Space Conditioning Alternatives Seminar, Austin, Texas, 1991.

"Influence of provenance and burial history on diagenesis of the Frontier Formation, Green River Basin, Wyoming": presented to the Bureau of Economic Geology Seminar, Austin, Texas, 1992.

"Geologic controls on reservoir properties of low-permeability sandstone, Travis Peak Formation, East Texas": presented to the Shreveport Geological Society, Shreveport, Louisiana, 1992.

"Porosity preservation by early siderite cementation in Canyon sandstones, Val Verde Basin, West Texas": presented to Department of Geology, Baylor University, Waco, Texas, 1993.

"Petrography and diagenesis of the Sonora Canyon Sandstone": presented to Conoco, Inc., Austin, Texas, 1994.

"Influence of early siderite cementation on reservoir quality in Sonora Canyon sandstones, Val Verde Basin, southwest Texas": presented to the Bureau of Economic Geology Seminar, Austin, Texas, 1994.

"Early, methanic-zone precipitation of siderite cement in submarine-fan sandstones, Val Verde Basin, Texas": presented to The University of Texas at Austin, Department of Geological Sciences, Technical Sessions, Austin, Texas, 1994.

"Diagenesis of Lower Cretaceous Travis Peak Formation, East Texas Basin": presented to The University of Texas at Austin, Department of Geological Sciences, Gulf of Mexico Sedimentary Basin Seminar (Geology 391), Austin, Texas, 1994.

R. J. Finley

"Depositional framework, reservoir character, and rock properties of the Travis Peak (Hosston) Formation, East Texas Basin": presented to the East Texas Geological Society, Tyler, Texas, 1985.

"Depositional framework, reservoir character, and rock properties of the Travis Peak (Hosston) Formation, East Texas Basin": presented to the Dallas Geological Society, Dallas, Texas, 1985.

"Depositional framework, reservoir character, and rock properties of the Travis Peak (Hosston) Formation, East Texas Basin": presented to Friends of the Mesozoic, Houston, Texas, 1985.

"Depositional framework, reservoir character, and rock properties of the Travis Peak (Hosston) Formation, East Texas Basin": presented to the Shreveport Geological Society, Shreveport, Louisiana, 1985.

"Geology and reservoir characteristics of tight gas sandstones in the Travis Peak Formation, Chapel Hill field, East Texas": presented to the Houston Geological Society, Houston, Texas, 1988.

"Tight gas sandstones": presented to the School on Fundamentals of Petroleum Engineering for employees of Schlumberger, sponsored by the Department of Petroleum Engineering, The University of Texas at Austin, 1986.

Results of GRI-sponsored research on depositional framework of the Travis Peak presented to visiting geologists involved in a project to drill and fracture horizontal wells in tight gas sandstone, Bureau of Economic Geology, Austin, Texas, 1987.

M. A. Fracasso

Results of GRI-sponsored stratigraphic research presented to a delegation of scientists from the Beijing Graduate School, East China Petroleum Institute, Beijing, China PRC, Bureau of Economic Geology, Austin, Texas, 1986.

H. S. Hamlin

"Frontier Formation stratigraphy and sandstone geometry, Green River Basin, Wyoming": presented to the Bureau of Economic Geology Seminar, Austin, Texas, 1990.

"Stratigraphy of Canyon Sandstone, Val Verde Basin": presented to the Bureau of Economic Geology Seminar, Austin, Texas, 1993.

"Tight gas case studies: lessons from Frontier stratigraphic studies": presented to Gas Strategy Team, Chevron U.S.A., Austin, Texas, 1993.

"Stratigraphy of Canyon sandstones, Val Verde Basin" and "Ozona Canyon sandstones: Val Verde Basin": presented to the Bureau of Economic Geology Seminar, Austin, Texas, 1993.

"Geology of Canyon sands tight-gas reservoirs, Val Verde Basin": presented to the North Texas Geological Society, Wichita Falls, Texas, 1994.

"Regional stratigraphic mapping issues and log character and correlations, Wilcox Lobo trend, South Texas" and "Production statistics and controls on productivity, Wilcox Lobo sandstones, South Texas": presented to Wilcox Lobo operators, Houston, Texas, 1994.

"Canyon sandstone: key research issues": presented at Canyon Play Management of Technology meeting, sponsored by the Texas Independent Producers and Royalty Owners Association and the Gas Research Institute, Midland, Texas, 1994.

"Geologically complex gas reservoirs in slope and basin facies, Canyon sandstones, Val Verde Basin, southwest Texas": presented to the Society of Independent Professional Earth Scientists, Austin, Texas, 1994.

"Geologically complex gas reservoirs in slope and basin facies, Canyon sandstones, Val Verde Basin, southwest Texas": presented to the American Institute of Professional Geologists and the Oklahoma Geological Survey, Norman, Oklahoma, 1995.

"Wolfcamp sandstones in Pakenham field, Terrell County: resource technologies": presented to Chevron U.S.A. Production Company, Midland, Texas, 1995.

"Lobo sandstone study: challenges and goals": presented to Wilcox Lobo operators, Houston, Texas, 1995.

"Review of previous Canyon sandstone research and presentation of new research plan": presented to Canyon and Wolfcamp sandstones operators, Midland, Texas, 1995.

T. F. Hentz

"Evidence for eustatic and tectonic control on the sequence stratigraphy of the Upper Pennsylvanian Cleveland Formation, western Anadarko Basin": presented to the Bureau of Economic Geology Seminar, Austin, Texas, 1992.

"Evidence for eustatic and tectonic control on the sequence stratigraphy of the Cleveland Formation, a tight gas sandstone in the western Anadarko Basin": presented to the North Texas Geological Society, Wichita Falls, Texas, 1993.

"Sequence stratigraphy of the Middle to Upper Pennsylvanian Cleveland and Marmaton siliciclastics, western Anadarko Basin, Texas Panhandle": presented to the North Texas Geological Society, Wichita Falls, Texas, 1993.

"Regional diagenesis, reservoir hydrodynamics, and hydrochemical-facies and gas-composition mapping of the Wilcox Lobo trend, South Texas": presented to Wilcox Lobo operators, Houston, Texas, 1994.

"Key-well concept and other aspects of stratigraphic analysis of the Wilcox Lobo play": presented to Wilcox Lobo operators, Houston, Texas, 1995.

"Regional overview of the structure and depositional facies of the Cleveland Formation": presented to the Cleveland Development Forum, sponsored by the Society of Petroleum Engineers, Society of Professional Well Log Analysts, Panhandle Geological Society, and Amarillo Geophysical Society, Amarillo, Texas, 1995.

M. L. W. Jackson

Structural history of the Sabine Arch and its relation to hydrocarbon traps": presented to the East Texas Geological Society, Tyler, Texas, 1992.

Structural history of the Sabine Arch and its relation to hydrocarbon traps": presented to the Shreveport Geological Society, Shreveport, Louisiana, 1993.

S. E. Laubach

Presentations and participation in roundtable discussions at the DOSECC-Project GUIDE workshop for a proposed ultradeep continental borehole at the Balcones Research Center, The University of Texas at Austin. This meeting attracted an international audience. Talks based on GRI-sponsored research presented at this workshop were titled "Measurement of loading-induced strain in sedimentary basins" and "A suggested origin for Late Cretaceous–early Tertiary arches of the Gulf of Mexico," 1986.

Results of GRI-sponsored structural geology research presented to a delegation of scientists from the Beijing Graduate School, East China Petroleum Institute, Beijing, China PRC, at the Bureau of Economic Geology, Austin, Texas, 1986.

Results of GRI-sponsored structural geology research presented to visiting geologists involved in a project to drill and fracture horizontal wells in tight gas sandstone, Bureau of Economic Geology, Austin, Texas, 1987.

"Fractured reservoirs: lessons from the Travis Peak Formation": presented as a series of lectures to graduate class in reservoir analysis, Department of Geological Sciences, The University of Texas at Austin, 1988.

"Natural fracture history of the Travis Peak Formation": presented to the Center for Tectonophysics, Texas A&M University, 1988.

"Analysis of fractures and in situ stress in reservoir rocks": Department of Geological Sciences, The University of Texas at Austin, 1989.

"Application of borehole-imaging logs to fracture evaluation in low-permeability gas reservoirs" and "Origin, distribution, and effect on production of natural fractures in a low-permeability gas reservoir with extensive quartz cement": presented to the Society of Petroleum Engineers, Naturally Fractured Reservoir Forum, Crested Butte, Colorado, 1989.

"Aspects of geologic and geophysical evaluation of subsurface fractures": presented to Norsk Hydro a.s. Research, Bergen, Norway, 1989.

"Current research on prediction of fractures": presented to the Exxon Production Research Company, Houston, Texas, 1989.

"Analysis of in situ stress and fractures in reservoir rocks": presented to graduate reservoir geology seminar, Department of Geological Sciences, The University of Texas at Austin, 1990.

"Current views of fracture development in rock": presented to the Bureau of Economic Geology Seminar, Austin, Texas, 1991.

"Geologic aspects of fractured reservoir characterization": presented to the Forum on Improved Oil & Gas Recovery sponsored by TIPRO and the Bureau of Economic Geology, San Antonio and Longview, Texas, 1991.

"Pitfalls of fracture interpretation using borehole-imaging logs": presented to the Houston Westside Society of Professional Well Log Analysts, Houston, Texas, 1991.

"Fracture patterns in reservoir rocks": presented to the Fort Worth Geological Society, Fort Worth, Texas, 1992.

"Unraveling the relationship between fractures and diagenesis": presented to the Lawrence Berkeley National Laboratory Earth Science Division, Berkeley, California, 1992.

"Opportunities for horizontal drilling in fractured low-permeability sandstones, United States:" presented to the Horizontal Drilling Symposium, Denver, Colorado, 1992.

"Challenge: improved prediction of fracture attributes in reservoir rocks": presented to the Gas Research Institute Fracture Research Workshop, Austin, Texas, 1992.

"Summary of issues pertaining to detection and characterization of fractures in the subsurface": presented to the Gas Research Institute—Bureau of Economic Geology Natural Fracture Workshop, Austin, Texas, 1993.

"A new national report on geology and engineering aspects of tight gas sandstones": presented to the Gas Research Institute Project Advisors Group meeting, Oklahoma City, Oklahoma, 1993.

"Natural fractures in Sonora Canyon sandstones, Sonora and Sawyer fields, Sutton County, Texas": presented to the 1993 Society of Petroleum Engineers Rocky Mountain Regional and Low-Permeability Reservoir Symposium, Denver, Colorado, 1993.

"Complex natural gas reservoirs": presented at Gas Research Institute Project Advisors Group meeting, Golden, Colorado, 1994.

"Fracture, fault, and stress-pattern issues of the Wilcox Lobo trend, South Texas": presented to Wilcox Lobo operators, Houston, Texas, 1994.

"Improved resource characterization technology using new structural methods": presented to the Gas Research Institute Project Advisors Group meeting, Grand Junction, Colorado, 1995.

"Improved resource characterization technology: overview of project": presented to the Gas Research Institute Project Advisors Group meeting, Chicago, Illinois, 1995.

"Fracture and diagenesis analyses applicable to Canyon Sandstone": presented to Canyon and Wolfcamp sandstones operators, Midland, Texas.

"Introduction to new research project in Wilcox Lobo play": presented to Wilcox Lobo operators, Houston, Texas, 1995.

"Introduction and concept for new fracture analysis approach" and "Using a new classification of diagenesis to predict fracture conductivity": presented at Fracture Quantification working group meeting, Fort Worth, Texas, 1995.

"Geology of the Wilcox Lobo natural gas trend, South Texas" presented to the Texas Railroad Commission, Austin, Texas, 1995.

"Using diagenesis information to improve interpretation of natural fractures": presented to The University of Texas at Austin, Department of Geological Sciences Soft Rock Seminar, Austin, Texas, 1995.

"Natural gas fracture detection using cathodoluminescence": presented at the Gas Research Institute Geology Technical Advisory Group meeting, Austin, Texas, 1995.

"Gas research program overview": presented at the Siberian oil and gas managers' training program, Austin, Texas, 1995.

Workshops

The Bureau of Economic Geology hosted a Fracture Research Workshop in 1987, in Austin, Texas. Bureau researchers and other contractors working on the characterization and design of fractures presented preliminary research results to an audience that included industry representatives.

Dutton, S. P., and Finley, R. J., presented "Core Workshop: Travis Peak (Hosston) Formation, East Texas" to the School on Fundamentals of Petroleum Engineering for employees of Schlumberger, sponsored by the Department of Petroleum Engineering, The University of Texas at Austin, 1986.

Dutton, S. P., and Hamlin, H. S., presented "Geology of the Frontier Formation" to the Gas Research Institute, *Tight Gas Sands Program—Frontier Formation Workshop*, Denver, Colorado, 1990.

Dutton, S. P., presented "Geology of the Travis Peak Formation and Cotton Valley Group, East Texas" to the Gas Research Institute, *East Texas Cotton Valley and Travis Peak Formations Workshops*, Tyler and Houston, Texas, 1990.

Finley, R. J., and Dutton, S. P., presented two sections of "Core workshop: Travis Peak (Hosston) Formation, East Texas" to the Shreveport Geological Society, Shreveport, Louisiana, 1985.

Hamlin, H. S., presented "Geologic overview of the Enron South Hogsback cooperative well" to the Gas Research Institute Workshop, *A Case Study of a Cooperative Well Project in the Frontier Formation, Moxa Arch, Green River Basin, Wyoming*, Denver, Colorado, 1991.

Hamlin, H. S., presented "Geology of the Canyon Sands tight gas reservoirs" to the Gas Research Institute/Society of Petroleum Engineers Workshop, *Results of Applied Research in the Canyon Sands*, Midland, Texas, 1992.

Hamlin, H. S., and Laubach, S. E., presented "Frontier Formation stratigraphy, diagenesis and natural fracturing" to the Gas Research Institute/ Society of Petroleum Engineers Workshop, *Conclusions of GRI Research in the Frontier Formation*, Casper, Wyoming, 1992.

Laubach, S. E., and Hamlin, H. S., presented a field trip workshop "Fractures in the Frontier Formation" to the Rocky Mountain Sectional Meeting, American Association of Petroleum Geologists, 1992.

Laubach, S. E., presented "Structural geology of the Travis Peak Formation" to the Gas Research Institute, *Forum on Staged Field Experiment No. 1*, 1987.

Laubach, S. E., presented "Geological overview of Staged Field Experiment No. 2" to the Forum on the *Relationship between Rock Mechanical Properties and Acoustic Well Log Data*, Lakeway, Texas, May 1988.

Laubach, S. E., presented "Stratigraphy, diagenesis, and structure of the Travis Peak Formation and their effects on reservoir quality" to the Gas Research Institute, *SFE No. 2 Workshop: Techniques of Comprehensive Evaluation and Completion of Tight Gas Sands*, in association with the Gas Technology Symposium, Society of Petroleum Engineers, Dallas, Texas, 1989.

Laubach, S. E., presented "Fracture studies of sandstone, chalk, and coal" during a short course titled *Identifying and Interpreting Fractures*, sponsored by the Houston Geological Society for the Gulf Coast Association of Geological Societies Conference, Houston, Texas, 1991.

Laubach, S. E., presented "Core and outcrop observations of fracture attributes" to the Society of Exploration Geophysicists Workshop, *Geophysical Methods of Fracture Detection*, Houston, Texas, 1991.

Laubach, S. E., presented "Regional state of stress and hydraulic fracture azimuth in the western Green River Basin" to the Gas Research Institute/Society of Petroleum Engineers Workshop, *Conclusions of GRI Research in the Frontier Formation*, Casper, Wyoming, 1992.

The Bureau of Economic Geology hosted a GRI Natural Fracture Research Workshop in 1992, in Austin, Texas. Panels of experts on natural fracture research discussed current and future natural fracture research before an audience of about 70 industry representatives.

The Bureau of Economic Geology, Gas Research Institute, and West Texas Geological Society cosponsored a workshop "Geology and production aspects of a stratigraphically complex natural gas play: Canyon Sandstone, Val Verde Basin, Texas," held in 1994 in Midland, Texas. Bureau researchers presented research results to an audience of more than 350 industry representatives.

The Bureau of Economic Geology hosted a symposium and workshop on new methods to characterize natural fractures in 1996 in Austin, Texas. In addition, five separate workshops were held for industry participants in project research during 1995–1996. In all, more than 300 participated.

Acknowledgments

This work was supported by the Gas Research Institute under contract number 5082-211-0708. Donations of cores, well logs, and other data by numerous companies and operators form an important part of the data base for the studies carried out in this project and are gratefully acknowledged. Tucker F. Hentz contributed to the preparation of this report. The work summarized here benefited from discussions and ideas shared by many individuals at the Bureau of Economic Geology, the Gas Research Institute, other GRI contractor organizations, other research groups (including the state surveys of Wyoming and Colorado), and industry. Word processing, typesetting, and layout were by Susan Lloyd.