DEFINING COALBED METHANE EXPLORATION FAIRWAYS IN EAST-CENTRAL TEXAS

by

Roger Tyler and Andrew R. Scott

prepared for
the U.S. Geological Survey
under cooperative agreement no. 99HQAG0018

Bureau of Economic Geology
W. L. Fisher, Director *ad interim*
The University of Texas at Austin
Austin, Texas 78713-8924

December 1999

The following report relies extensively on information previously published in

Ayers, W. B., Jr., and Lewis, A. H., 1985, The Wilcox Group and Carrizo Sand (Paleogene) in East-Central Texas: depositional systems and deep-basin lignite: The University of Texas at Austin, Bureau of Economic Geology Geological and Hydrological Folio 1, 19 p., 30 pls.

CONTENTS

Figures

ABSTRACT

The Bureau of Economic Geology, The University of Texas at Austin, has developed a basin-scale coalbed methane producibility and exploration model based on a decade of Gas Research Institute–supported research performed in the San Juan, Sand Wash (Greater Green River), and Piceance Basins and on reconnaissance studies of several other producing and prospective coal basins in the United States. As part of a cooperative agreement between the Bureau of Economic Geology (BEG) and the U.S. Geological Survey (USGS), BEG is to provide a preliminary assessment of the coalbed methane potential of the east-central Texas Gulf Coast coal basins based on previously published literature and data. The objective of this report is to discuss the application of the producibility model in defining coalbed methane exploration fairways in an east-central Texas coal basin. The producibility model indicates that tectonic/structural setting, depositional systems and coal distribution, coal rank, gas content, permeability, and hydrodynamics are controls critical to coalbed methane producibility. However, simply knowing a basin's geologic and hydrologic characteristics will not lead to a conclusion about coalbed methane producibility because it is the interplay among geologic and hydrologic controls on production and their spatial relation that governs producibility. High producibility requires that the geologic and hydrologic controls be synergistically combined. That synergism is evident in a comparison of the prolific producing San Juan Basin and marginally producing Sand Wash and Piceance Basins, where high productivity is governed by (1) thick, laterally continuous coals of high thermal maturity; (2) adequate permeability; (3) basinward flow of ground water through coals of high rank and gas content orthogonally toward no-flow boundaries (regional structural hingelines, fault systems, facies changes, permeability contrasts, and/or discharge areas); (4) generation of secondary biogenic gases; and (5) conventional trapping along those boundaries to provide additional gas beyond that generated during coalification. Understanding the dynamic interaction among these key

geologic and hydrologic controls will be critical for delineation of exploration fairways in east-central Texas frontier basins and for targeting "sweet spots" along the Gulf Coast.

INTRODUCTION

Methane from coal beds is a potentially important source of natural gas, but to date successful exploration and exploitation of coalbed methane resources have been limited along the Texas Gulf Coast (fig. 1). Triggered by success in the low-rank coals of the Powder River Basin, Rocky Mountain Foreland, exploration for coalbed methane has begun in low-rank, coal-rich areas of the Gulf Coast. What has not been widely recognized about the Rocky Mountain Foreland experience is that although coalbed methane resources in some basins have been successfully exploited, other basins with seemingly similar geologic and hydrologic attributes have proven to be disappointing methane producers (Tyler and others, 1997).

The traditional view of production from coal reservoirs is inadequate to explain these contrasts in coalbed methane producibility among coal basins. In the traditional view, coal gases are generated in situ during coalification and are sorbed onto the coal's large internal surface area. Sorption is pressure dependent and is promoted by increasing pressure. Gas production is then achieved by reducing reservoir pressure through depressuring (dewatering), thereby liberating the gases from the coal surface for diffusion to the cleat system for subsequent flow to the wellbore. The traditional view is oversimplified because it fails to recognize that in prolific producing coalbed methane basins, there is a need for migrated and trapped sources of gas beyond that generated during coalification to achieve high gas contents found in many basins. Importantly, migrated conventionally and hydrodynamically trapped gases, in situ–generated secondary biogenic gases, and solution gases are required to achieve these high gas contents or fully gas-saturated coals for consequent high productivity (Scott and others, 1994a). To delineate the presence and origin of these additional sources of gas requires an understanding of the interplay among tectonic and

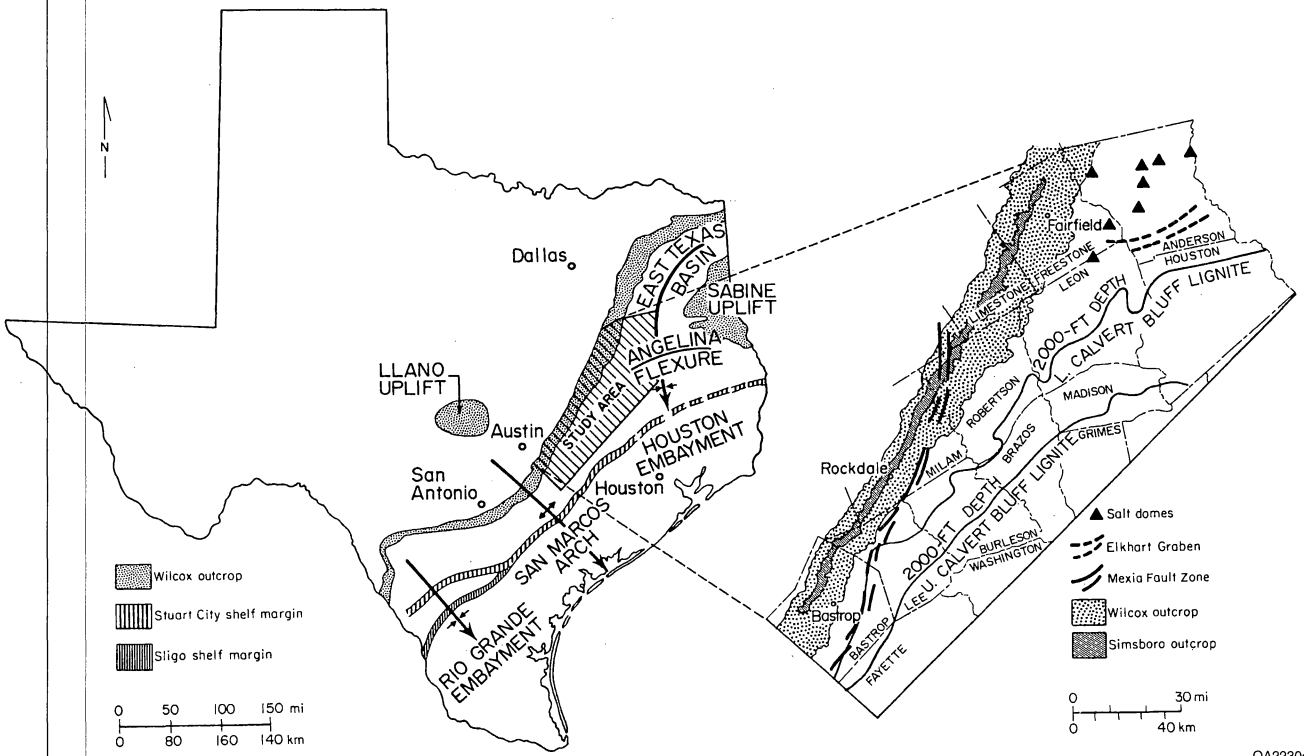


Figure 1. Location of the east-central Texas coal basin evaluation and proposed exploration fairway. Structural elements that affected early Tertiary coal sedimentation are modified from Ayers and Lewis (1985). Basin analysis and an integrated drilling program will provide relevant data to Texas operators to define exploration fairways and currently underexploited gas resources (app. A).

structural setting, depositional systems and coal distribution, coal rank, gas content, permeability, and hydrodynamics (fig. 2) (Kaiser and others, 1995).

Our understanding of the controls on coalbed methane producibility is based on comprehensive geologic and hydrologic studies of the San Juan, Sand Wash, and Piceance Basins and reconnaissance studies of several other producing and prospective coal basins in the western United States and Alaska (fig. 3) (Tyler and others, 1991, 1994, 1995a, b, c, 1996, 1997). The San Juan Basin, in which cumulative production exceeds 1 Tcf (28 Bm^3), is the world's most prolific coalbed methane basin. Our basin-scale model for coalbed methane producibility has evolved out of a comparison of the prolific San Juan and marginally producing Sand Wash and Piceance Basins. The comparison is apt because these basins share similar geologic and hydrologic attributes but in dissimilar combination (fig. 4). Prior to development efforts, the Sand Wash and Piceance Basins were viewed as being potentially very productive, but subsequent drilling and production efforts showed them to be poor to moderate producers. To date, Sand Wash Basin coals have yielded large volumes of water and little gas, and Piceance Basin coals, little water and limited gas. Below is a discussion of the producibility model and key criteria for coalbed methane resource evaluation. This is followed by a review of the geologic and hydrologic controls on coalbed methane producibility along the Gulf Coast.

COALBED METHANE PRODUCIBILITY MODEL

Coalbed methane producibility is determined by the synergistic interplay among six critical controls: tectonic/structural setting, depositional systems and coal distribution, coal rank, gas content, permeability, and hydrodynamics (fig. 2). Unfortunately, coalbed methane exploration strategies are often based only on the location of the greatest net coal thickness and highest coal rank, and explorationists largely ignore the interplay among hydrologic and geologic factors affecting coalbed methane producibility, leading to widespread exploration failure. An understanding of these controls in a frontier exploration play with limited production, combined

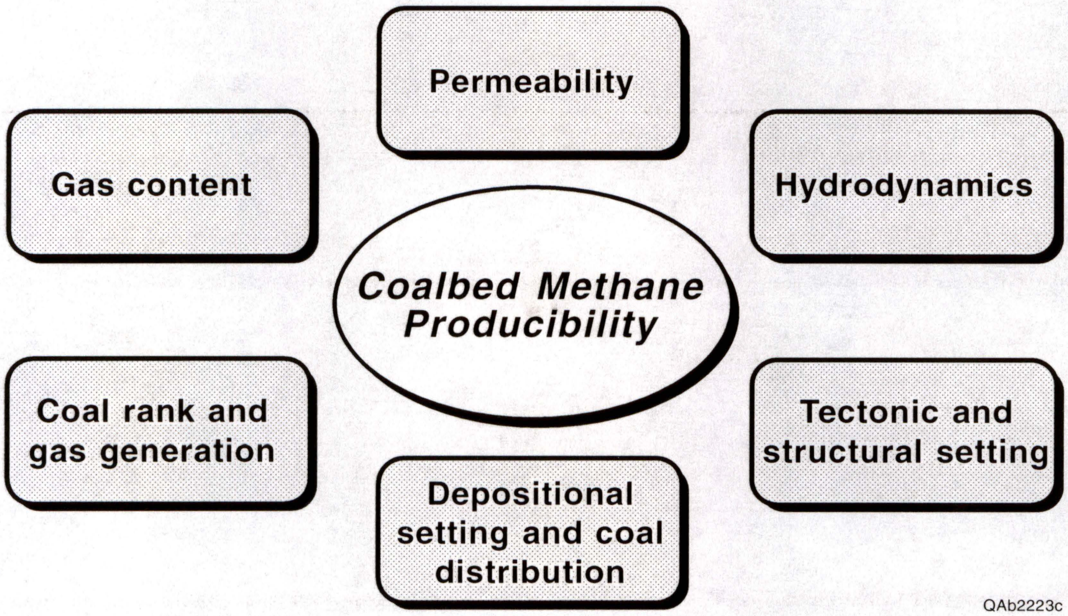


Figure 2. Geologic and hydrologic controls critical to coalbed methane producibility. Synergistic interplay among these controls and their spatial relations governs producibility.

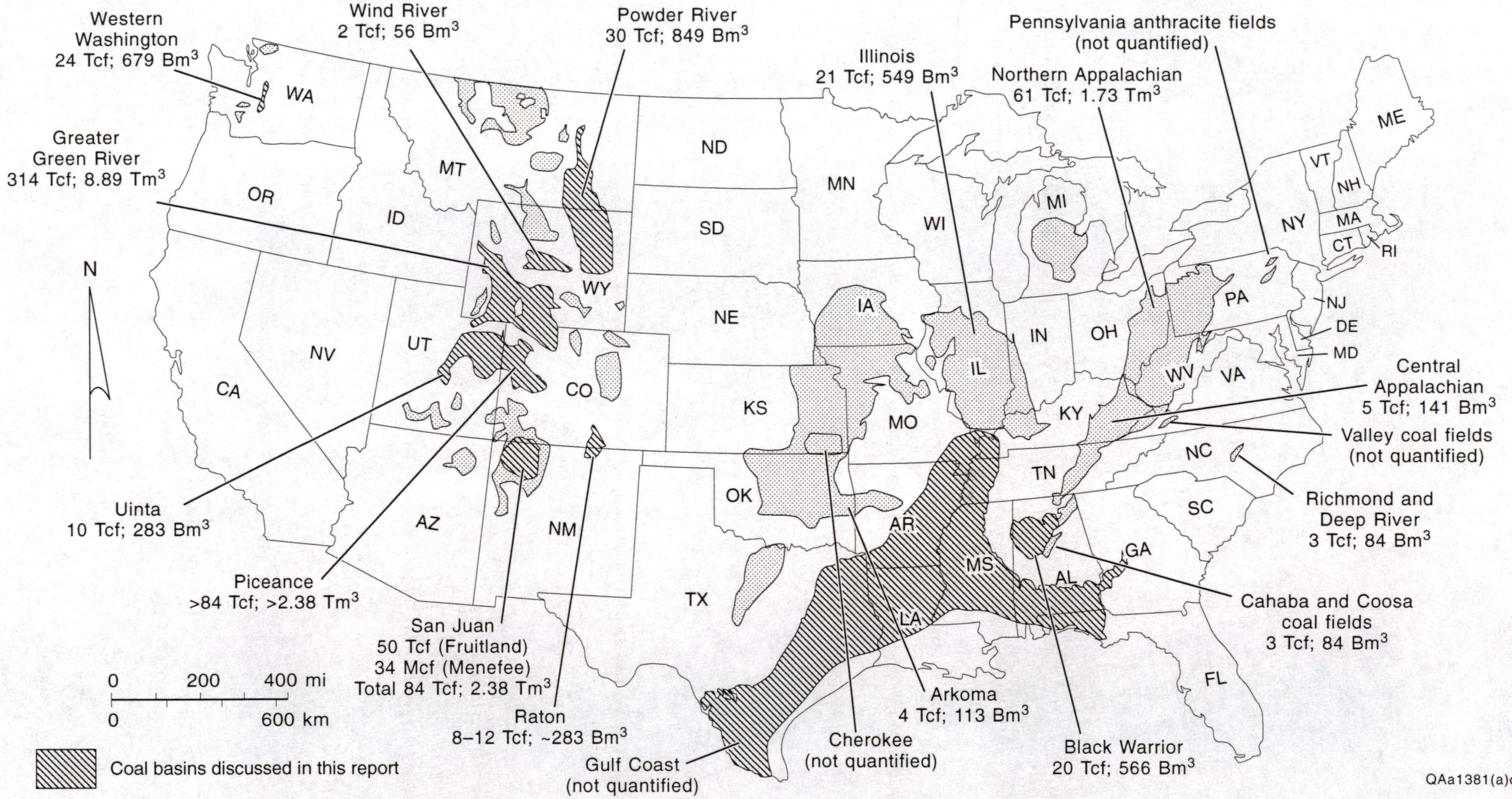


Figure 3. Coal basins and coalbed methane resources of the United States. Total coalbed methane is estimated to exceed 675 Tcf (Scott and others, 1994a). Our understanding of the controls on coalbed methane producibility is based on comprehensive geologic and hydrologic studies of the San Juan, Greater Green River (Sand Wash), and Piceance Basins and reconnaissance studies of Raton, Powder River, Uinta, Wind River, and Western Washington coal basins in the western United States. Because of the low-rank coals, Texas has not been included in the coalbed methane resource estimates.

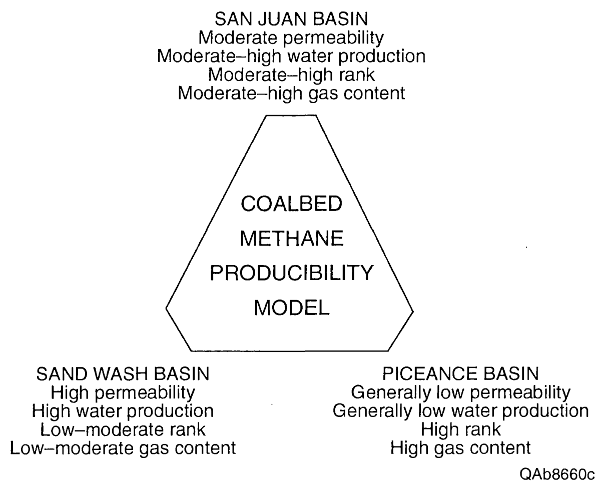


Figure 4. Ternary basin comparison for coalbed methane model development. In the San Juan and Sand Wash Basins, permeability is moderate to high and ground-water flow is dynamic, whereas the Piceance Basin is a low-permeability, hydrocarbon-overpressured basin having sluggish flow or static conditions.

with an understanding of their interplay, can lead to more accurate prediction of coalbed methane producibility.

Coal beds are both the source and reservoir for methane, indicating that their widespread distribution within a basin is critical to establishing a significant coalbed methane resource. Coal distribution is closely tied to the tectonic, structural, and depositional settings because peat accumulation and preservation as coal require a delicately balanced subsidence rate that maintains optimal water-table levels. Depositional systems define the substrate upon which peat growth is initiated and within which the peat swamps proliferate. Knowledge of depositional framework enables prediction of coalbed thickness, geometry, and continuity and, therefore, areas of potential coalbed methane resources. Existing Bureau of Economic Geology knowledge of the depositional systems in Texas and available data for east-central Texas have enabled a more accurate prediction of coalbed thickness, geometry, and continuity and, therefore, areas of potential coal gas resources.

Coals must also reach a threshold of thermal maturity (vitrinite reflectance values between 0.8 and 1.0 percent; high-volatile A bituminous) before significant volumes of thermogenic gases are generated. The amount and types of coal gases generated during coalification are a function of burial history, geothermal gradient, maceral composition, and coal distribution within the thermally mature parts of a basin. Although higher rank coals generally have higher gas contents, gas content is not determined by coal rank alone; gas content is not fixed but changes when equilibrium conditions within the reservoir are disrupted. Importantly, there is a need for additional sources of gas beyond that generated initially during coalification to achieve high gas contents following basinal uplift and cooling. In figure 5a and 5b, sorption isotherms show the increase in methane sorption with increasing pressure. At higher temperatures (T1) (dashed line), coals store less gas; migration occurs when gas generation exceeds coal-storage capacity. Gas generation decreases with basinal uplift and cooling (T2) (solid line), resulting in coal beds that are undersaturated with respect to methane. Secondary biogenic gas generation and migration of thermogenic and biogenic gases in meteoric water can resaturate the coals with methane (fig. 5b). When coals are fully

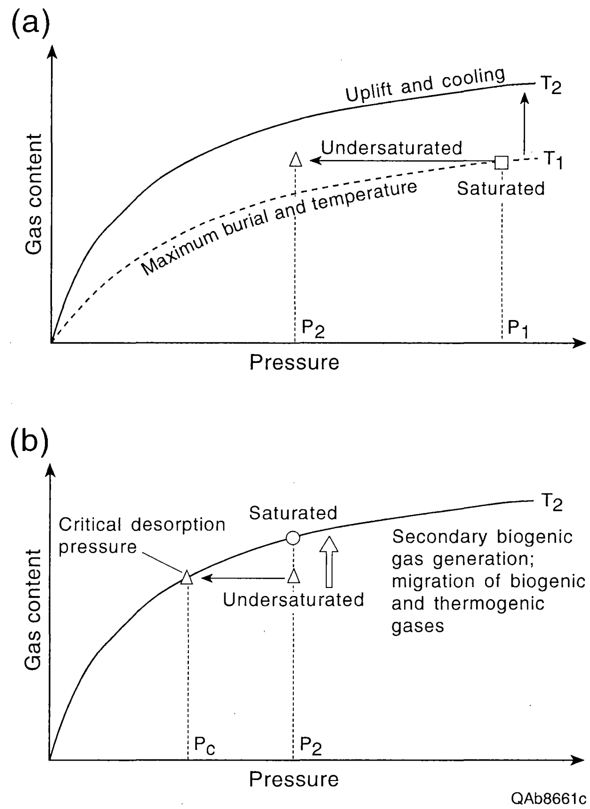


Figure 5. Sorption isotherms showing relation between gas content, pressure, and temperature (from Scott and others, 1994a). (a) At high temperatures, coals store less gas. (b) Upon uplift and cooling, gas generation slows and coals become undersaturated with respect to methane. Secondary biogenic gas and migrated thermogenic and biogenic gases can resaturate coals with gas. (P1T1: Pressure and temperature during active gas generation; P2T2: Pressure and temperature after basinal uplift and cooling; Pc: Critical desorption pressure).

saturated, the critical pressure at which desorption occurs is high, requiring less depressuring (dewatering) and recovery of more methane (Scott and others, 1994a). Coals with gas contents below the sorption isotherm are undersaturated with respect to methane (fig. 5b). Undersaturation indicates that reservoir pressure must be decreased until a critical desorption pressure (Pc) is reached, at which point gas production begins. Gas contents on the isotherm indicate that the coal is saturated with respect to methane; gas production will begin with minimal decrease in reservoir pressure. Oversaturated coals have coal gas in the cleat system and will produce gas immediately upon perforation.

Gas content of coals can therefore be enhanced, either locally or regionally, by generation of secondary biogenic gases or by diffusion and long-distance migration of gases to no-flow boundaries such as permeability contrasts, structural hingelines, or faults for eventual resorption and conventional trapping. Areas of enhanced gas content or saturation generally require laterally extensive, permeable coals to serve as conduits for gas migration and dynamic ground-water flow to promote migration of gases. Further, flushing of coal beds by meteoric water in areas of active recharge or convergent flow can decrease gas content, as can uplift and erosion, which lower the reservoir pressure, allowing methane to desorb from the coal surface. Importantly, secondary biogenic gases have made a significant contribution to produced gases in the San Juan and Powder River Basins; most of the produced coal gases in the lower rank coals of the Powder River Basin are migrated and/or secondary biogenic, and more than 300 Bcf of secondary biogenic gas is estimated to have been produced in the San Juan Basin (Scott and others, 1994a). In Texas, evaluation of the chemical and isotopic composition of produced gases will be an indicator of the gas origin and of its thermal and migration histories.

Permeability and ground-water flow are intimately related to coal distribution and depositional and tectonic/structural setting because basinward flow of ground water through coal beds requires recharge of laterally continuous permeable coals at the structurally defined basin margins. Permeability in coal beds is also determined by its fracture (cleat) system, which is in turn largely controlled by the tectonic/structural regime. Cleats are the permeability pathways for migration of gas and water to the producing well, and cleats may either enhance or retard the success of the coalbed methane completion. The coals, therefore, act not only as conduits for gas migration but also are commonly ground-water aquifers that may have permeabilities orders of magnitude larger than associated sandstones. However, permeability that is too high results in high water production and decreased gas saturation in many basins. Consequently, high permeability may be as detrimental to the economic production of coalbed gas as extremely low permeability.

Importantly, understanding the dynamic interaction among key geologic and hydrologic controls is the basis for delineation of exploration fairways in frontier basins or sweet spots in basins with established or limited production. Extraordinary production requires dynamic ground-water flow through coals of high thermal maturity (rank) and high gas content orthogonally toward flow barriers, accompanied by generation of secondary biogenic gas and conventional trapping of migrated and solution gases along those barriers (Kaiser and others, 1994a) (fig. 6). The resulting interplay leads to high gas contents or even fully gas-saturated coals for consequent high productivity. In other words, the parts of a frontier play or basin having the best potential for coalbed methane production should be those basinward of where outcrop coals are in good hydraulic communication with subsurface coals for consequent generation of secondary biogenic gas, advective gathering and transport of thermogenic gas, and subsequent basinward resorption and conventional trapping, which promote fully gas-saturated coals and high production.

Using this coalbed methane producibility model and an understanding of the synergistic interplay among controls that can be used to define exploration fairways, exploration and development can now proceed to the Texas Gulf Coast.

APPLICATION OF THE PRODUCIBILITY MODEL TO TEXAS

In Texas Gulf Coast coal basins, simply knowing the basin's geologic and hydrologic characteristics will not lead to a conclusion about coalbed methane producibility because it is the interplay among geologic and hydrologic controls on production and their spatial relation that

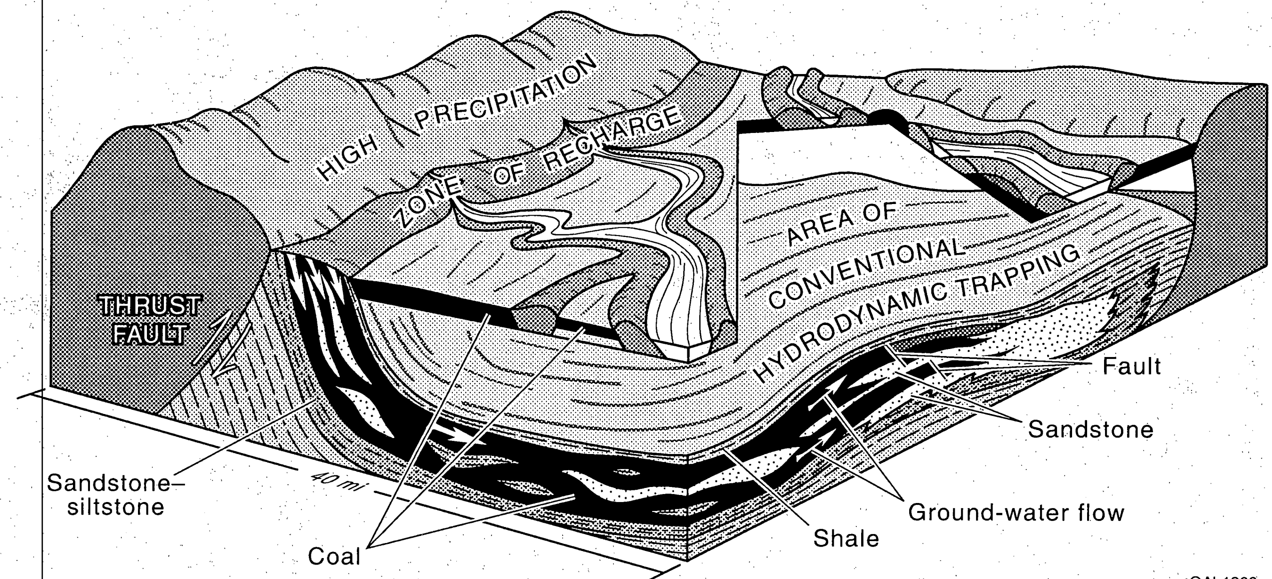


Figure 6. Conceptual model for high coalbed gas producibility based on the prolific producing San Juan Basin and marginally producing Sand Wash and Piceance Basins. High productivity is governed by (1) thick, laterally continuous coals of high thermal maturity; (2) adequate permeability; (3) basinward flow of ground water through coals of high rank and gas content orthogonally toward no-flow boundaries (regional hingelines, fault systems, facies changes, and/or discharge areas); (4) generation of secondary biogenic gases; and (5) conventional trapping along those boundaries to provide additional gas beyond that generated during coalification.

governs producibility (Kaiser and others, 1994a). High producibility in Texas requires that controls be synergistically combined. Importantly, permeability, hydrodynamics, coal distribution and rank, gas content, and tectonic and structural setting control the producibility of coal gases. High productivity requires that these geologic and hydrologic controls be synergistically combined. That synergism is evident in a comparison of the prolific San Juan Basin and marginally producing Sand Wash and Piceance Basins. In the San Juan Basin, ground water flows through high-rank, high-gas-content coals orthogonally toward lower rank coals at a no-flow boundary or flow barrier along a structural hingeline. At this point in the basin, flow turns upward and coalbed wells typically produce >1,000 Mcf/d (>28 Mm^3/d) and small volumes of water. A combination conventional and hydrodynamic trap is postulated to exist along the hingeline and implies that free, migrated, and solution gas is an important source of coal gas (fig. 6). In the Sand Wash Basin, flow is through low-rank, low-gas-content coals toward areas of higher thermal maturity. Lack of seals and permeability contrasts limits the potential for conventional trapping of gas in the basin. In the Piceance Basin, net coal is thickest in a north-south-trending belt, behind west-east-prograding shoreline sequences. Depositional setting and thrust faults cause coals along the Grand Hogback and in the subsurface to be in modest to poor reservoir and hydraulic communication. Meteoric recharge and flow basinward are thus restricted; permeability of coals and of sandstone in the basin is generally in the microdarcy range, indicating that meteoric recharge is limited to basin margins. Moreover, extraordinary coalbed methane production is precluded by the absence of dynamic ground-water flow. The best potential for coalbed methane production in the Piceance Basin may lie in conventional traps basinward of where outcrop and subsurface coals are in good hydraulic communication.

Understanding the reasons for these contrasts in producibility is applicable to Texas Gulf Coast coalbed methane exploration and development. By using the coalbed methane producibility model, it is now possible to understand the geologic and hydrologic synergism needed for coalbed methane production. Understanding this synergism can lead to more accurate prediction of Texas Gulf Coast coalbed methane fairways. As part of the report, this producibility model will be applied to the evaluation of coal gas resources of the deep-basin coal trends of the Wilcox Group, east-central Texas. The coal gas producibility model will consider all geologic and hydrologic criteria and data available. Coal gas producibility will be evaluated through six critical factors: tectonic/structural setting, depositional systems and coal distribution, coal rank, gas content, permeability, and hydrodynamics. Productivity within the east-central Texas coal basin will be governed by (1) thick, laterally continuous coals; (2) adequate permeability; (3) flow of ground water toward no-flow boundaries (regional hingelines, fault systems, facies changes, and/or discharge areas); (4) generation of secondary biogenic gases; and (5) conventional trapping along those boundaries to provide additional gas beyond that generated in situ during coalification. We think the coal gas research has progressed to the point where basin analysis, that is, understanding the dynamic interaction among these key geologic and hydrologic factors, can be used to define areas that may have coal gas producibility.

Statement of the Problem in Texas

Texas is ranked as one of highest (fifth) coal-producing states in the nation, but precious little is known about its coalbed methane potential. Coal production in Texas is entirely from surface mines in lignite and subbituminous coal, but Texas also has a tremendous resource of deeper, higher rank coal seams in both the Gulf Coast Basin and the Eastern Shelf of the Midland Basin. The potential for coalbed methane production from these deeper coal seams has yet to be realized and has not been evaluated because, until recently, coal seams in Texas were not considered exploration targets because of the low ranks of the coal. However, coalbed methane is an important hydrocarbon resource base in the United States, with recent estimates totaling 675 Tcf and, importantly, accounting for at least 6 percent of the total U.S. gas production. Traditionally, because of low coal ranks, coalbed methane has remained a largely underevaluated and underutilized resource in Texas. Operator interest in coalbed methane resource development in the lower rank coals of Texas, however, has increased dramatically over the past few years. The interest has escalated because of significant coalbed methane exploration and production successes in the low rank coals of the Powder River Basin, Wyoming, where total coal gas production from the subbituminous coals has increased to 150 MMcf per day in 1999 (from 1,000 wells), and is projected to increase to 300 MMcf per day in 2000 (Natural Gas Week, June 14, 1999).

Within the Texas Gulf Coast coal basin, there is a lack of publicly available coalbed methane data on the potential for exploration fairways, including limited gas content, gas and water geochemistry, and hydrodynamic evaluations of coal basins. These data could be obtained and evaluated with a limited program of new data acquisition and frontier exploration. Initial research developing a coalbed methane producibility model has been accomplished. The next phase in the development of the coalbed methane resources in Texas is detailed basin analysis and reservoir characterization including drilling and testing of the "sweets spots." Drilling and testing of the coalbed methane sweet spots should be accomplished with the cooperation of independent Texas gas operators who can provide additional appropriate data and information for complete evaluation of the coalbed methane potential of Texas.

Benefits to the drilling, exploration, and development program, will be the profitable recovery of coalbed methane, which should be encouraged for use in Texas as an alternative source of energy. Using available technologies, the operators can capture methane in coal basins to use or sell as an alternative energy source or to repressurize mature oil fields. If the State of Texas could provide information about the benefits of methane recovery by undertaking a cooperative drilling, exploration, and development program it will encourage companies to develop projects that capture the energy currently underexploited in Texas. However, the project must first develop mechanisms to attract other investors and to raise the awareness of profitable coalbed methane recovery opportunities in Texas, by communicating the value of coalbed methane recovery to other parties and relevant government agencies, so as to create the momentum for development. This report is the initial investment in a sequence of events that will lead to the drilling, exploration, and development of coalbed methane in Texas.

Research Objectives

More recent insights into coalbed methane exploration and development indicate that migrated conventionally trapped gases, in situ–generated secondary biogenic gases, and solution gases are required to achieve high gas contents or fully gas-saturated coals for consequent high productivity (Scott and others, 1994a). To delineate the presence and origin of these additional sources of gas in east-central Texas will require a detailed geologic and hydrologic basin analysis and drilling program that will include an understanding of the interplay among depositional systems and coal distribution, coal rank, gas content, hydrodynamics, and tectonic and structural setting, through well site data gathering, drilling, and exploration. The research objectives of this program in east-central Texas are to (a) evaluate geologic and hydrologic controls on coalbed methane producibility, (b) encourage and promote additional exploration and development of coalbed methane, (c) communicate the value of coalbed methane recovery so as to create a momentum for future exploration and development, and (d) digitize maps of the Ayers and Lewis (1985) study, compatible with NCRDS, for use in the coalbed methane resource assessment. To completely evaluate the coalbed methane potential of east-central Texas coal basin, it is proposed that in the future an advanced reservoir characterization program (1) screen data for potential production fairways, (2) cooperate with operators to test the quantity and attributes of gas in coal seams, and (3) evaluate coal rank and the chemical and isotopic compositions of gas produced in these basins to determine gas origin. This regional reservoir characterization evaluation will provide the independent Texas operators with baseline information, and it may stimulate development of a new gas resource in Texas.

Status of Coalbed Methane Research in East-Central Texas

Little emphasis has been placed on the lower rank coals of Texas because the coals were thought to be of such a lower rank that they would not be able to generate significant quantities of gas. With the successful development program of the low-rank coals of the Powder River Basin, where secondary biogenic and migrated gases play a very important role in exploration, this study will focus on the Wilcox Group (Paleocene and Eocene) of the Texas Gulf Coast. Numerous independent operators have inquired about the coalbed methane potential of these areas and the potential for migrated and secondary biogenic gases being a significant resource in Texas. They have reported natural gas "kicks" when drilling through coal seams and have expressed interest in testing the seams. Importantly, the producibility models indicate that thermogenic, migrated thermogenic, and secondary biogenic gas will play a more important role in resource development than previously expected in Texas. The Texas Gulf Coast coals may have the potential for development, given these newly developed exploration models for coal gas producibility.

Importantly, along the Texas Gulf Coast, Kaiser (1974) and Ayers and Lewis (1985) reported extremely large coal (lignite) resource estimates in the undivided Wilcox Group of Central Texas to a depth of 5,000 ft (1,524 m) below sea level. In those reports, deep-basin coal resources are estimated at 37,216 million tons (33,762 metric tons) in three main stratigraphic intervals: lower Calvert Bluff, upper Calvert Bluff, and Hooper. Given these resource estimates, can these stratigraphic intervals be considered major targets for coal gas resource development? Furthermore, Kaiser and others (1980) also calculated the lignite resources for all lignite-bearing units in the Texas Gulf Coast Basin and demonstrated that the deep-basin lignite resources are greatest in east-central Texas, where approximately 44 percent of Wilcox deep-basin resources and 30 percent of total deep-basin lignite will be found in Texas. On the basis of these resource evaluations, the Wilcox Group in east-central Texas was chosen as the focus of this project because it reportedly contains the largest quantity of deep-basin (220 to 2,000 ft [61 to 610 m]) coal (lignite) in Texas (Kaiser and others, 1980; Ayers and Lewis, 1985) and potentially could hold large coalbed methane resources (fig. 1). Moreover, operators who have reported "gas kicks" in these deeper coal seams should also be made aware that the potential exists to produce enough gas to lift oil from productive sandstones to the surface and then, after separation, to fire the heater treater and/or the pumping unit (Echols, 1995).

APPLICATION OF THE PRODUCIBILITY MODEL TO THE EAST-CENTRAL TEXAS COAL BASIN

Introduction

The Wilcox Group (fig. 7) in east-central Texas (Ayers and Lewis, 1985, pl. 1*) is the focus of this study because (1) it contains the largest quantity of deep-basin (200 to 2,000 ft [61 to 610 m]) coal resources in Texas (Kaiser and others, 1980), (2) the region is strategically located near several cities (fig. 1) that may use the deep-basin coal as an energy source, (3) the region has an existing gas-producing infrastructure, and (4) field tests of in situ gasification have been conducted on deep coal seams of the Wilcox Group (Ayers and Lewis, 1985). In east-central Texas, Ayers and Lewis (1985) estimated that the deep-basin lignite resources in the Wilcox Group of east-central Texas are 6,548 million tons (5,940 million metric tons) in seams greater than or equal to 5 ft (1.5 m) thick, between the depths of 200 and 2,000 ft (61 and 610 m). Because of these significant coal resources, coalbed methane exploration should focus on three stratigraphic intervals: the lower Calvert Bluff, which contains 78 percent of the coal resources, and the Hooper and upper Calvert Bluff, which possess 14 and 7 percent, respectively, of the coal resources.

The tectonic and structural setting, depositional systems, and coal distribution sections of this evaluation are based primarily on the work and text of Ayers and Lewis (1985) in east-central Texas. Depositionally, Ayers and Lewis (1985) stated that the early Tertiary Wilcox Group and the Carrizo Sand were deposited by fluvial-deltaic systems that prograded into the Houston Embayment from two directions. Primary basin fill was from the northwest by the Rockdale fluvial-deltaic system, which drained much of the Rocky Mountain foreland region. Secondary fill was from the north and northeast by a smaller fluvial system that was directed down the axis of the subsiding East Texas Basin (Ayers and Lewis, 1985). Moreover, the distribution of Wilcox coal

*All Ayers and Lewis (1985) plates referred to in this report, can be found in digital format on the disks provided.

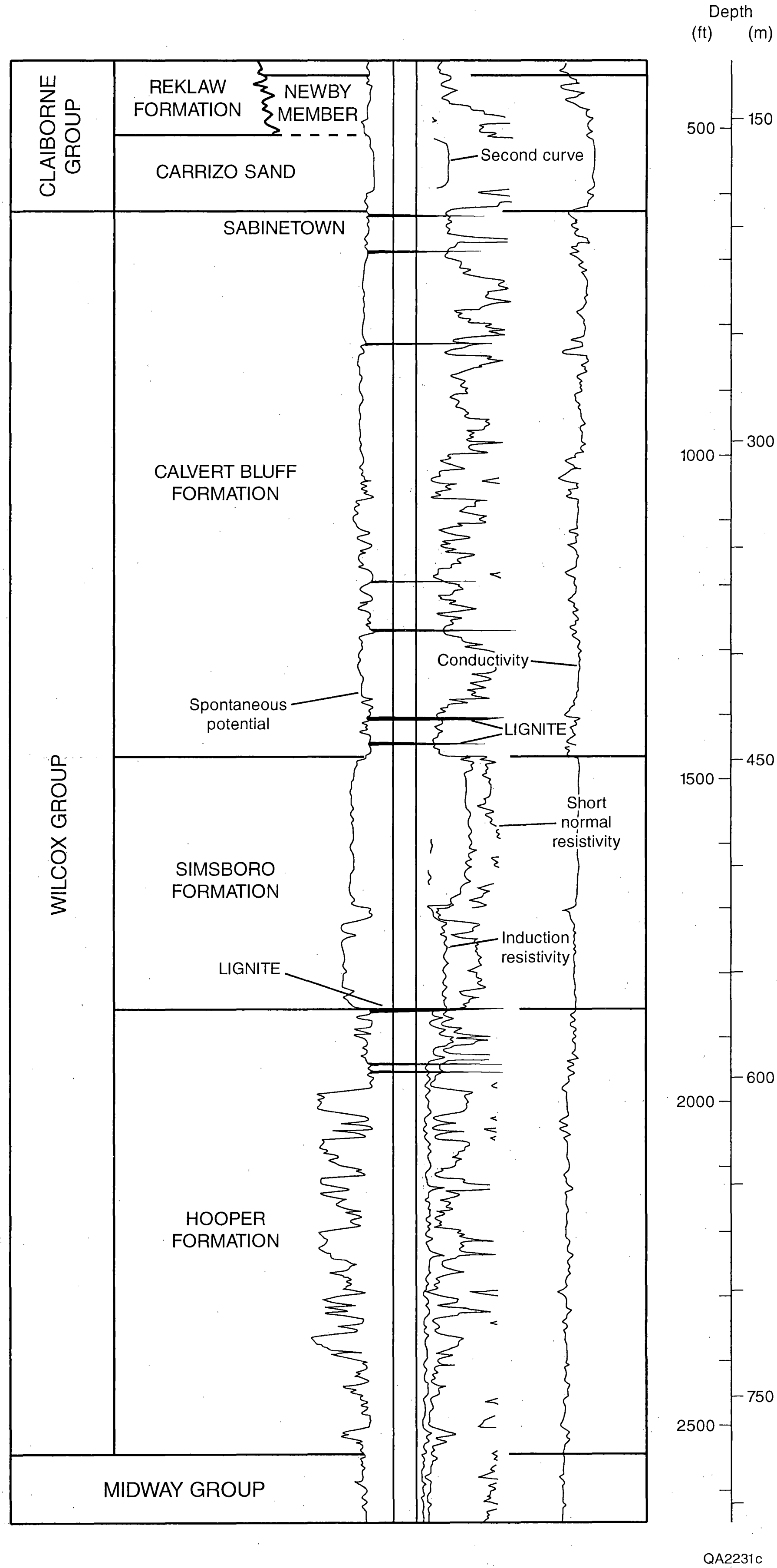


Figure 7. Composite type log for the Wilcox Group and Carrizo Sand in east-central Texas. Modified from Ayers and Lewis (1985).

seams is facies controlled (Fisher and McGowen, 1967; Kaiser, 1974; Kaiser and others, 1978). In the 200-to-2,000-ft (61-to-610-m) depth interval, for example, Calvert Bluff (fig. 7) coal seams in east-central Texas occupy a floodplain setting between paleofluvial channel complexes. Therefore, regional maps of the Wilcox sandstone depositional systems will aid in establishing coal distribution and in planning coalbed methane exploration. Furthermore, hydrologic investigations and resistivity mapping by Payne (1968, 1975), Ayers and others (1984), and Ayers and Lewis (1985), as well as ground-water modeling by Fogg and others (1983b) and Dutton (1999), demonstrate that the depositional framework elements serve as preferred avenues for ground-water flow. The Wilcox Group and the overlying Carrizo Sand (fig. 7) are major freshwater aquifers (Dutton, 1999). Although exploitable coal seams occur primarily in low-sand (floodplain) areas, the chances of intersecting framework channel sands under greater fluid pressure increase with depth. If such a sand complex is breached during coalbed methane exploration, the chances for success are diminished. Therefore, regional delineation of the tectonic and structural setting, coal distribution, depositional systems, and hydrodynamics is of great importance in establishing the coalbed methane potential of east-central Texas and in hydrologic evaluation of the movement of ground water and the likelihood of encountering large aquifers to the detriment of field-scale development of coalbed methane resources.

Tectonic and Structural Setting

East-Central Texas

The San Marcos Arch is southwest of the study area, and the axis of the Houston Embayment and East Texas Basin crosses Houston and Anderson Counties on the northeast (fig. 1). Because the study area is updip of the Stuart City shelf margin, the Wilcox has not been affected by major growth faults. Regionally, basinward dip on the base of the Wilcox (Ayers and Lewis, 1985, pl. 2) increases southwestward along strike from 45 to 55 ft/mi (9 to 10 m/km) in Anderson County to 214 ft/mi (41 m/km) in Bastrop and Fayette Counties, resulting in a narrowing of the deep-basin coal exploration fairway to the south (fig. 1). The rate of basinward thickening of the Wilcox Group (Wilcox isopach map, Ayers and Lewis, 1985, pl. 3) also increases southwestward, but less significantly, from 43 ft/mi (8 m/km) on the northeast to 58 ft/mi (11 m/km) on the southwest.

Examples of syndepositional and postdepositional faulting are seen in the Wilcox and Carrizo sandstones. The Mexia Fault Zone (fig. 1, Ayers and Lewis, 1985, pl. 2) is a compound graben system that is based in the wedge-out zone of the Louann Salt or in the lower part of the Smackover Formation; it was active from the Jurassic or Triassic through at least the Eocene (Jackson, 1982). From Bastrop County, the Mexia Fault Zone extends northeastward to cross the Wilcox outcrop in Robertson County. Syndepositional faulting is inferred from the increased thickness of the Wilcox Group (Ayers and Lewis, 1985, pl. 3) and the Carrizo Sand (C. M. Jones, personal communication with Ayers, 1983) in Lee County. Subtle control of fluvial-deltaic trends of the Rockdale delta system by the Mexia Fault Zone is inferred (compare isopach trends with sand-body trends on lithofacies maps [Ayers and Lewis, 1985, pls. 4 and 5]). Considerable postdepositional faulting (in places as much as 600 to 800 ft [185 to 245 m] of vertical displacement) where the Mexia Fault Zone crosses the deep-basin fairway in Lee, Burleson, Milam, and Robertson Counties offsets thick coal seams and may also affect basinward movement of ground water in the Wilcox and Carrizo aquifers.

The Elkhart Graben (fig. 1 and Ayers and Lewis, 1985, pl. 2), which formed by crustal stretching and collapse over salt pillows, has a history of movement from the Cretaceous through the Quaternary (Jackson, 1982). Because the graben is oriented normal to the Wilcox paleofluvial system, movement along it did not affect Wilcox lithofacies trends. Carrizo Sand thicknesses, however, may have been influenced (C. M. Jones, personal communication, 1983). Furthermore, postdepositional faulting may affect the movement of ground water through the Carrizo Sand and offset coal seams in the Wilcox.

The origin and evolution of the East Texas Basin were summarized by Jackson (1981) and by Seni and Kreitler (1981). An unpublished isopach map and sand-body trends mapped in earlier studies (Ayers and Lewis, 1985; Kaiser and others, 1978) demonstrate that subsidence coeval with sedimentation influenced the thickness of preserved sediments and the trends of Wilcox and Carrizo fluvial systems. These fluvial systems are directed toward the axis of the East Texas Basin. Within the basin, depositional trends were further influenced by salt tectonics. Wilcox fluvial systems skirted active salt domes and flowed through the associated peripheral sinks, leaving sediments that are commonly 8 to 40 percent thicker than those in unaffected areas (Seni and Jackson, 1983).

East-Central Texas Coal Basin Structural Evaluation

Incorporating the work of Ayers and Lewis (1985) with our producibility model points to a potential exploration fairway south of the Mexia fault zone. The potential coalbed methane exploration fairway is located where conventional trapping of (1) updip migrated thermogenic gas, (2) migrated secondary biogenic gases, and (3) solution/free gas may occur.

Structurally, the east-central Gulf Coast Basin area occurs dowdip from the major faulted graben that may act as both the permeability barrier to fluid flow in the updip (gas) and/or downdip (water and secondary biogenic gas) direction. Depth to the main Wilcox coal-bed producing intervals is favorable (approximately 2,000 to 6,500 ft; 610 to 1,980 m). The Wilcox total thickness of between 2,000 and 3,500 ft (610 and 1,067 m) of gross section, containing multiple coal and sandstone reservoirs, is also favorable. Migration of gases from existing Wilcox gas fields within the east-central Gulf Coast Basin is also a favorable contribution to coalbed methane resource development. The evaluation of gas migrating in sandstones should also be included in any gas resource evaluation of the area. Experience in the Piceance Basin, Rocky Mountain Foreland has shown that in many instances dually completing wells in both sandstone and coal can make the coalbed methane exploration fairway economic, even at depths greater than 6,000 ft (1,850 m).

Natural fracture systems (coal cleat) and in situ stresses are unknown attributes in the east-central Gulf Coast Basin area. Coal cleat acts as the permeability pathway for migration of both the gas and the water to the wellbore, and coal cleat attributes need to be recorded to determine the permeability of the reservoir in the drilling and exploration program. It is noted that the lignites at surface coal mines in the area are cleated.

Depositional Systems and Coal Distribution

Previous Regional Coal Depositional Studies

Earlier studies (Culbertson, 1940; Echols and Malkin, 1948; Fisher and McGowen, 1967, Ayers and Lewis, 1985) show that the Wilcox Group constitutes a thick wedge of fluvial-deltaic sediments that records the earliest progradation into the Tertiary Gulf Coast Basin. Within the east-central Texas study area, Echols and Malkin (1948) identified the Rockdale delta, which, as demonstrated by Fisher and McGowen (1967), is composed of many individual delta lobes. Updip of the Rockdale delta system, Fisher and McGowen (1967) described the Mount Pleasant fluvial system, which fed sediments to the Rockdale deltas. They suggested that coal seams associated with the Mount Pleasant fluvial system are elongate and laterally adjacent to channel sands, whereas coal seams associated with the Wilcox deltaic facies are tabular and either are of local extent, having formed in an interdistributary setting, or are areally more extensive, having developed across abandoned deltas.

Depositional Systems

This section of the report is based on the regional lithofacies maps and text by Ayers and Lewis (1985) for the Hooper, Simsboro, and Calvert Bluff Formations of the Wilcox Group and for the Carrizo Sand of the Claiborne Group (figs. 1 and 7), where they assessed lithofacies control of coal distribution and ground-water movement. Ayers and Lewis (1985) mapped the maximum sand (the single thickest sand) and the net thickness and percentage of major sands (those greater than 40 ft [12 m] thick) identified on geophysical well logs. Maximum- and major-sand maps delineate the depositional systems. Framework sands control the occurrence of coal (Kaiser and others, 1978) and the movement of ground water (Payne, 1968, 1975; Ayers and others, 1984; Ayers and Lewis, 1985).

Hooper Formation

The Hooper Formation (fig. 7) is an upward-coarsening sequence that records a succession from prodelta through distributary-channel fill, delta-plain mudstone, and coal. It documents initial progradation of Wilcox fluvial-deltaic systems into the Houston Embayment. The base of the Hooper was placed at the bottom of the lowest Wilcox upward-coarsening sequence of regional extent; stratigraphically lower progradational sequences, locally present in Anderson and Freestone Counties, were excluded to make the regional structural map (Ayers and Lewis, 1985, pl. 2).

On the major-sand isolith map (Ayers and Lewis, 1985, pl. 4), framework sands in the shallow subsurface compose elongate, basinward-flaring belts parallel to the paleoslope. Ayers and Lewis (1985) interpreted a fluvial depositional setting for the proximal facies and a deltaic setting for the distal facies. The junction of the alluvial and deltaic plains is closest to the outcrop at the southwest end of the region, and the fluvial-deltaic systems terminate at an embayed marine area (Garwood subembayment of Fisher and McGowen, 1967) in Bastrop County. Fluvial-deltaic systems over the southwestern three-fourths of the map radiate from a locus to the northwest. Channel-fill sands of the eastern one-fourth originate to the north and northeast and are funneled through the East Texas Basin (see "Simsboro Formation," below).

Simsboro Formation

On geophysical well logs Ayers and Lewis (1985, pls. 6 through 9 [not digitally provided]) documented that the Simsboro sand is recognizable by a blocky well log pattern and high formation resistivity. Basal contacts and, commonly, upper contacts are sharp. In the depositional axis near Rockdale (Ayers and Lewis, 1985, pl. 5), the Simsboro Formation is composed of predominantly medium- to coarse-grained sand (McGowen and Garner, 1970; Bammel, 1979), which was deposited by a bed- to mixed-load fluvial system (McGowen and Garner, 1970) that fed Wilcox deltas farther basinward (Fisher and McGowen, 1967). Suggested sources for the sediments are the Ouachita Mountains (Kohls, 1967) and the Rocky Mountains (Bammel, 1979). Two fluvial systems are delineated in the study (fig. 8; Ayers and Lewis, 1985, pls. 4, 5, and 10). Primary fluvial input from an inferred northwestern source entered the Wilcox coastal plain from a locus west of Waco and fed sediments to the Rockdale delta system (described by Fisher and McGowen, 1967); secondary fluvial input from the north and northeast flowed through the East Texas Basin and across the Angelina Flexure (Jackson, 1982) to feed smaller deltas east of the Rockdale delta system.

The axis of primary input extends approximately 75 mi (120 km) from Leon County southwest to the Garwood subembayment (described by Fisher and McGowen, 1967) in Bastrop County (fig. 8; Ayers and Lewis, 1985, pl. 5). Within the depositional axis, multistory, multilateral channel-fill sand complexes compose the Simsboro (Ayers and Lewis, 1985, pl. 6 [not digitally provided]). Few floodplain deposits are preserved, and coal seams, although present, are not of economic value because they are thin, discontinuous, and interbedded with thick water-bearing sands. Within the depositional axis, sand bodies are elongate parallel to the paleoslope in the shallow subsurface, but some bifurcation suggestive of an upper-delta-plain setting along the southeast margin exists in Leon and Madison Counties (Ayers and Lewis, 1985, pl. 5). On the southwest margin of the study area in Bastrop and Fayette Counties, sand-body geometry clearly defines a delta that prograded into the Garwood subembayment (Ayers and Lewis, 1985, pls. 5 and 10). This delta complex marks the southwestern flank of the Rockdale fluvial-deltaic system. The multistory, multilateral sands, characteristic of the Simsboro in the axis of the Rockdale fluvial-deltaic system, break up southwestward into this marginal delta complex and form

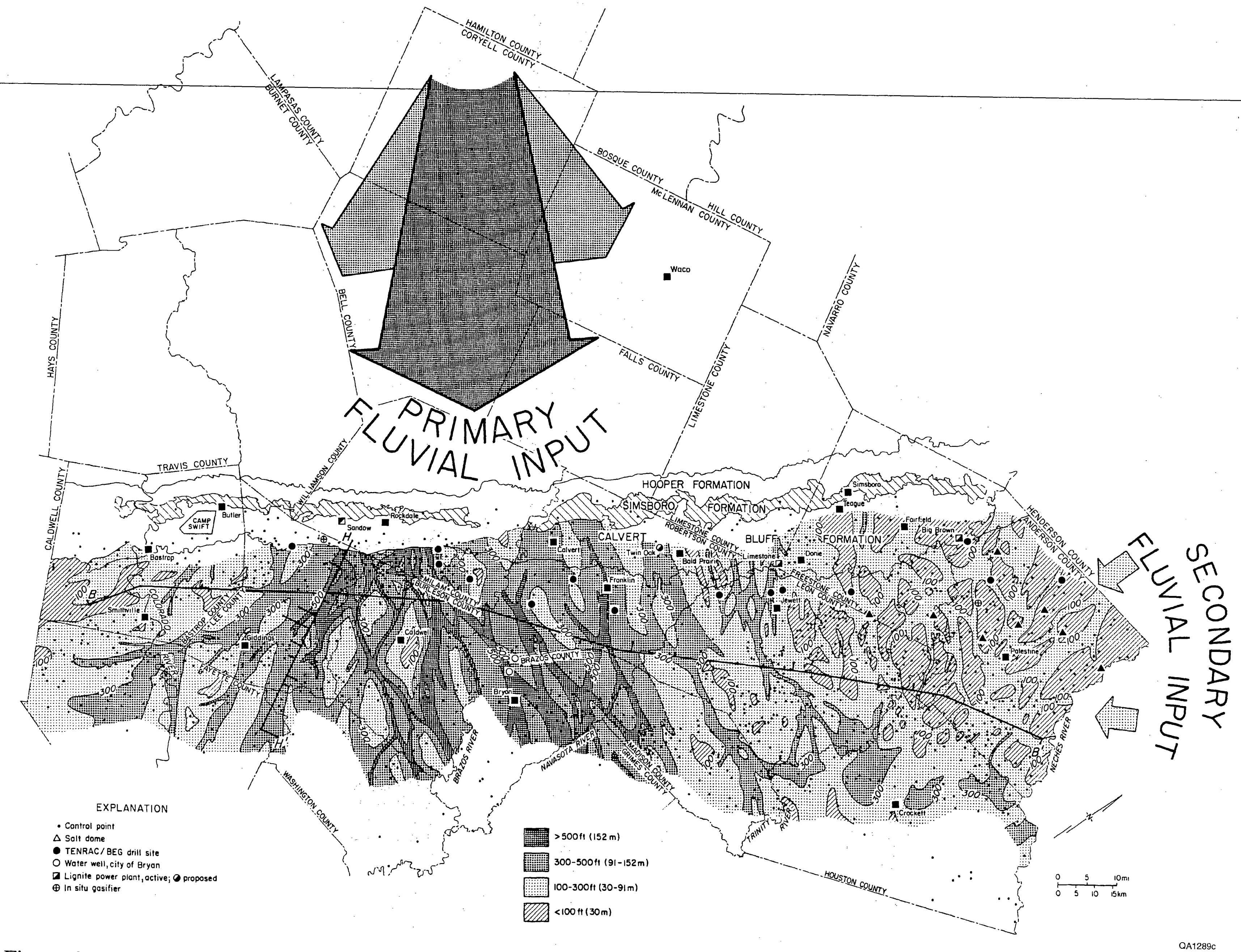


Figure 8. Isolith map of major sands (sands 40 ft [12 m] or thicker) for the Simsboro Formation, simplified from Ayers and Lewis (1985, pl. 5). The primary fluvial system entered the coastal plain from a locus west of Waco. Sources for the secondary fluvial system were to the north and northeast (from Ayers and Lewis, 1985).

multistory sands interbedded with overbank mudstone and coal (Ayers and Lewis, 1985, pl. 6 [not digitally provided]).

Similarly, the Simsboro breaks up into multistory channel-fill sand bodies northeast of the Rockdale depositional axis, in northeastern Leon County (Ayers and Lewis, 1985, pl. 5). In Anderson and Houston Counties, multistory channel-fill sands of the secondary fluvial system, stratigraphically equivalent to the Simsboro Formation, are nearly indistinguishable from the overlying Calvert Bluff sands (Ayers and Lewis, 1985) and the tripartite subdivision of the Wilcox Group is difficult to recognize. Northeast of the Trinity River, the Wilcox has previously been mapped as an undivided unit in the subsurface (Kaiser, 1978; Kaiser and others, 1978). Dip-elongate major-sand belts of the secondary fluvial system in Anderson and Houston Counties are oriented northwest-southeast, north-south, and northeast-southwest (Ayers and Lewis, 1985, pl. 5). These trends reflect the funneling effect of the actively subsiding East Texas Basin (fig. 1). Major-sand belts skirt active salt domes in Anderson County as described by Seni and Jackson (1983), exit the East Texas Basin across the Angelina Flexure (fig. 1), and appear to terminate in a series of small deltas in the northern Houston Embayment (Ayers and Lewis, 1985, pl. 5). These postulated small deltas are also apparent on the net major-sand map for the Hooper Formation (Ayers and Lewis, 1985, pl. 4).

Calvert Bluff Formation

The Calvert Bluff Formation is composed of interbedded coal seams, mudstones, and thin sandstones that encase multistory sands 50 to 100 ft (15 to 30 m) thick (fig. 7). The lower contact is commonly sharp on geophysical well logs, with lower Calvert Bluff mudstones and thick coal seams directly overlying massive Simsboro sands across the depositional axis of the Rockdale fluvial-deltaic system. In the shallow subsurface, the Carrizo Sand forms a sharp upper contact with the Calvert Bluff. The Sabinetown, a thin (generally less than 50 ft [15 m]) mudstone unit just below the Carrizo Sand, is included in the Calvert Bluff Formation (Ayers and Lewis, 1985).

Although the Calvert Bluff demonstrates persistence of sediment-input axes (compare Ayers and Lewis, 1985, pls. 11 and 12, with Simsboro and Hooper maps, pls. 4 and 5), the style of sedimentation changed abruptly from Simsboro to Calvert Bluff deposition in the axial region of the Rockdale fluvial-deltaic system. No longer were extensive Simsboro-type multilateral sand bodies formed. Instead, Calvert Bluff sand bodies were multistory and encased in abundant nonframework facies. With this abrupt change in sedimentary style, significant regions of the Calvert Bluff coastal plain were sufficiently isolated from coarse-grained fluvial sedimentation to allow the accumulation of the thick muds and peats (coal) that are characteristic of the lowermost Calvert Bluff (see "Lower Calvert Bluff Coal").

Sand-body geometry on the major-sand maps (Ayers and Lewis, 1985, pls. 11 and 12) is straight to meandering in the shallow subsurface. However, beginning approximately 10 to 15 mi (16 to 24 km) downdip of outcrop, a distributive pattern is common throughout much of the primary (Rockdale) fluvial-deltaic system. Lower alluvial and upper to lower deltaic plain, respectively, are the depositional settings inferred from these geometries (Kaiser, 1978). Therefore, the effect of the change in sedimentary style in the Rockdale fluvial-deltaic system is combined with an overall shift in depositional setting from dominantly alluvial plain with subordinate deltaic plain in the Simsboro during the maximum Wilcox regression (Kaiser, 1978) to a more deltaic setting in the Calvert Bluff. The abrupt change in sedimentary style across the entire Rockdale fluvial-deltaic system (Bastrop through Leon Counties) suggests either an extrabasinal control that decreased the rate of sediment input or an increase rate of basin subsidence; Ayers and Lewis (1985) prefer the former interpretation. Although sand-body geometry documents a fluvially dominated delta system with little evidence of destruction sands, thin low-resistivity units (interpreted as marine shales) are locally present within the Calvert Bluff, and a landward shift of depositional facies is apparent from the lithofacies maps (Ayers and Lewis, 1985, pls. 11 and 12). The Calvert Bluff terminates with a thin marine shale (Sabinetown), which represents a regional transgression over much of the east-central Texas study area.

Within the Rockdale fluvial-deltaic system, net thickness of major sands increases basinward to more than 400 ft (120 m) in distributary-channel axes (Fayette through Leon Counties) (Ayers and Lewis, 1985, pl. 11). Values are much lower (less than 300 ft [90 m]) in the secondary fluvial system of the East Texas Basin and Houston Embayment. There is little or no evidence of regional variation in the percentage of major sands for the Calvert Bluff Formation (Ayers and Lewis, 1985, pl. 12). Calvert Bluff sand-body trends in the East Texas Basin are similar to those of the Simsboro and Hooper.

Carrizo Sand

On cross section B–B′ (Ayers and Lewis, 1985, pl. 7 [not digitally provided]), a massive Carrizo sand in the updip region (well log GM-33) is in sharp (erosional) contact with the muddy upper Calvert Bluff (marine Sabinetown shale) (fig. 7). Reportedly, in the shallow subsurface in Anderson and northern Leon Counties (C. M. Jones, personal communication with Ayers, 1983) and at outcrop to the east in Cherokee County (Stenzel, 1951, 1953), the Sabinetown is absent and the Carrizo is in erosional contact with underlying upper Calvert Bluff sands and shales. Downdip (Ayers and Lewis, 1985, pl. 7, well log Q-59), Carrizo fluvial sands cap an upward-coarsening (progradational) sequence above the marine Sabinetown shale. In the Ayers and Lewis (1985) study the base of the Carrizo Sand was placed at the base of the massive sand (fig. 7). To follow subsurface practice and to facilitate correlation, the top of the Carrizo was placed at the top of an upward-fining sequence that is recognized as the Newby Member (transgressive marine sand) of the Reklaw Formation (Plummer, 1932; Stenzel, 1951, 1953). Because Ayers and Lewis (1985) mapped only major sands (those greater than 40 ft [12 m] thick) and maximum sands (the single thickest Carrizo Sand), the Newby is not reflected on lithofacies maps; it never constitutes a major or maximum sand.

The Carrizo, composed of moderately well to well-sorted fine to medium sand (Todd and Folk, 1957), is a major aquifer in east-central Texas. At outcrop it is a multistory, multilateral fluvial sequence deposited with the retreat of the Sabinetown sea (Plummer, 1932). Payne (1975) noted that Carrizo lithology is regionally more uniform than that of many other early Tertiary formations. Conventional isopach and sandstone-percentage maps, therefore, fail to delineate the framework elements; however, maps of the maximum sand and the net thickness of major sands (Ayers and Lewis, 1985, pls. 13 and 14) do so, and they disclose several differences between Carrizo and antecedent Wilcox depositional systems.

In the Rockdale fluvial-deltaic system, the depositional axis had shifted southward by Carrizo time; net thickness of major sands is greatest on the south flank of the system in Bastrop, Lee, and Fayette Counties and in the Garwood subembayment (Ayers and Lewis, 1985, pl. 14). Maximum-sand trends (Ayers and Lewis, 1985, pl. 13) in southern Bastrop County intersect the Yoakum Channel, an upper Calvert Bluff submarine canyon that down-cut and filled before Carrizo deposition (Hoyt, 1959; Vormelker, 1979). On cross sections by Hoyt (1959), the Carrizo Sand thickens rapidly into the Yoakum Channel; lower Carrizo log patterns are upward coarsening (progradational), whereas upper Carrizo patterns are blocky (aggradational). On the maximum-sand map (Ayers and Lewis, 1985, pl. 13), an embayed area extends from Washington to Madison County. In this region dip-oriented sands of the shallow subsurface may terminate in strike-oriented sand bodies (southeastern Lee County). Similar but better developed sand-body trends farther basinward are apparent on maps by Payne (1975) and suggest wave-dominated deltas.

The orientation of fluvial sand-body trends in Leon County has changed from east-west in the Calvert Bluff (Ayers and Lewis, 1985, pl. 12) to southeast-northwest in the Carrizo (Ayers and Lewis, 1985, pls. 13 and 14). In fact, this reorientation of fluvial systems is presaged on the isolith map for Calvert Bluff major sands (Ayers and Lewis, 1985, pl. 11), which shows complex trends in the region. This change resulted either from a tendency of the secondary fluvial system of the East Texas Basin to aggrade the coastal plain abandoned by the southward shift of the Rockdale fluvial system into the Garwood subembayment or from basinward migration of the shoreline during Carrizo sedimentation, or from both. Reduced thicknesses of both the maximum and net major sands where dip-oriented Carrizo Sand belts cross the Elkhart Graben (Ayers and Lewis, 1985, pls. 13 and 14) suggest a subtle structural control on deposition, possibly increased preservation of overbank sediments due to an increased rate of subsidence. C. M. Jones (personal communication, 1983) suggested that the Carrizo is thicker in the graben than over adjacent salt pillows.

Depositional Model

Wilcox and Carrizo lithofacies maps provide new insight for reconstruction of the early Tertiary paleogeography of the central United States (figs. 9A–9E, Ayers and Lewis, 1985). During the late Paleocene and early Eocene, the Gulf Coast Basin was filled by major delta systems in the Mississippi Embayment (Holly Springs delta system; Galloway, 1968), Houston Embayment (lower Wilcox Rockdale delta system; Fisher and McGowen, 1967), and Rio Grande Embayment (upper Wilcox Rosita delta system; Edwards, 1981). Unlike modern Gulf Coast delta systems, Paleogene systems of the western Gulf Coast (Rockdale and Rosita) were as large as, or larger than, that of the Mississippi Embayment (Holly Springs) (fig. 9A, Ayers and Lewis, 1985). Both the direction of sediment input and its timing, coincident with the climax of Laramide orogeny (Chapin and Cather, 1981; Ayers, 1984), led Ayers and Lewis (1985) to conclude that sediments for the former deltas were derived from Laramide uplifts to the northwest, as suggested by Winker (1982). Ayers and Lewis (1985) suggested that a major fluvial system fronting the Rocky Mountains flowed southward, collected the spillover from Laramide foreland basins, and deposited the sediment on the Eocene Texas Gulf Coast (fig. 9A). The source of the Holly Springs delta system was to the north and east. Not until the Miocene did epeirogenic uplift of the western United States cause great volumes of sediments to be shed eastward and the northern Rocky Mountain fluvial system to be diverted northeast of the Ouachita Mountains and into the Mississippi Embayment, thus increasing sediment input to the Mississippi Embayment at the expense of the Texas Gulf Coast. Additionally, the Neogene uplift of the western United States created an orographic rainfall effect that greatly reduced runoff on the east side of the Rockies and

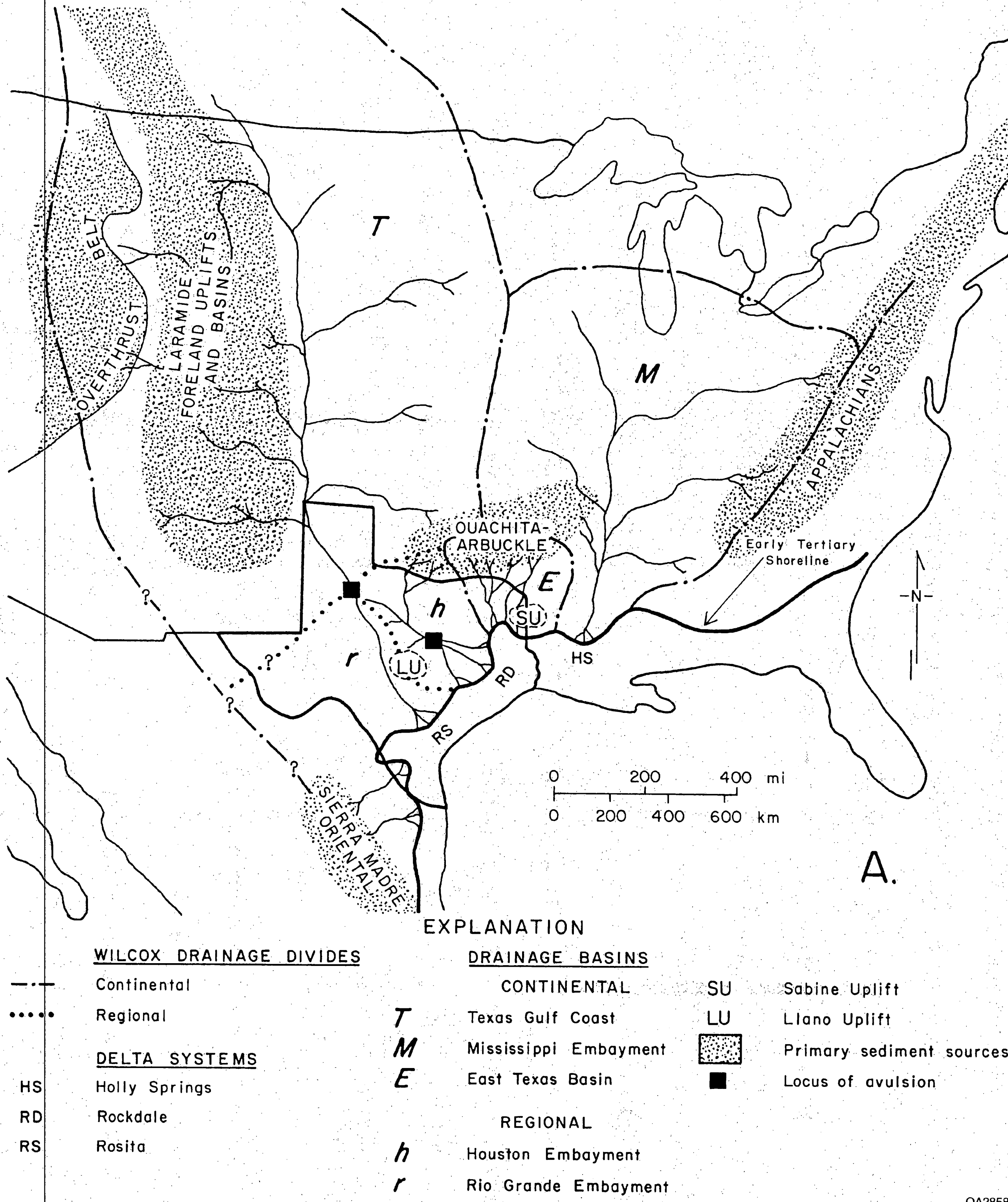
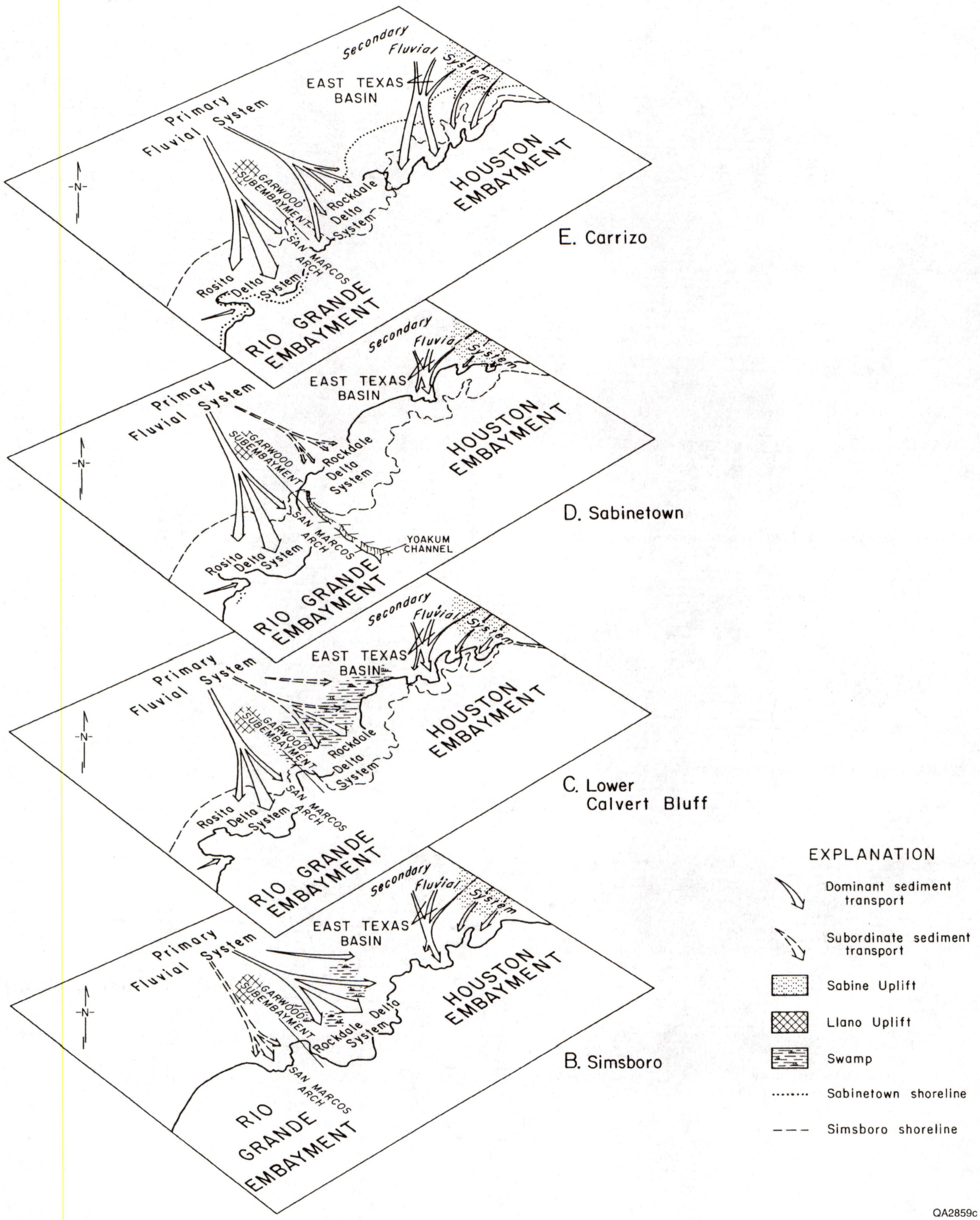


Figure 9. Postulated early Tertiary paleogeography: (A) Wilcox drainage basins and loci of avulsion of primary fluvial system; (B) Simsboro paleogeography—primary sediment input is north of the San Marcos Arch; (C) lower Calvert Bluff time—the primary fluvial system has switched south of the San Marco Arch and peat swamps spread across the foundering Rockdale delta; (D) Sabinetown transgression across the primary and secondary fluvial-deltaic systems in the Houston Embayment;



and (E) Carrizo regression—primary system progrades into the Rio Grande Embayment and the Garwood subembayment. Regional paleoslope is to the south. Simsboro and Sabinetown shorelines depict maximum Wicox regression and transgression, respectively, in the Houston Embayment.

resulted in further diminution of late Cenozoic deltaic processes on the western margin of the Gulf Coast Basin (Ayers and Lewis, 1985).

The major fluvial system that drained the Rockies is postulated to have episodically avulsed at a locus northwest of the Llano Uplift (fig. 9A, Ayers and Lewis, 1985) to feed either the Rockdale delta system of the Houston Embayment or the Rosita delta system of the Rio Grande Embayment. The Hwang Ho (Yellow) River of China (Dunbar and Rodgers, 1957) is suggested as a modern analog. It avulses at a nodal point 250 mi (400 km) inland and supplies sediment to either the Gulf of Po Hai or the Yellow Sea, 200 mi (320 km) to the south. Net-sand maps (Bebout and others, 1982) reveal a lower Wilcox depocenter north of the San Marcos Arch and an upper Wilcox depocenter south of the arch (figs. 10 and 11). Ayers and Lewis (1985) suggested that in early Wilcox time, fluvially dominated Rockdale deltas rapidly prograded basinward while marine processes dominated south of the San Marcos Arch (fig. 9B, Ayers and Lewis, 1985). Conversely, progradation of the upper Wilcox Rosita deltas south of the San Marcos Arch coincides with Calvert Bluff (including marine Sabinetown shale) deposition in the Rockdale delta system (figs. 9C and 9D, Ayers and Lewis, 1985). Ayers and Lewis (1985) proposed that the sharp change in style of sedimentation that marks the transition from the Simsboro to the Calvert Bluff Formation resulted from avulsion of the primary fluvial system southward from the Houston Embayment into the Rio Grande Embayment.

Sediment input to the Rockdale delta system from the smaller regional drainage basin (fig. 9A, Ayers and Lewis, 1985) and, perhaps, brief episodic input from the primary fluvial system were sufficient to continue aggradation of the proximal coastal plain, but at a much reduced rate. The reduced sediment input resulted in a multistory fluvial system that is indistinguishable from, and merges with, the secondary fluvial system of the East Texas Basin. Confinement of Simsboro multilateral sands by muds of the lower Calvert Bluff transformed the Simsboro into an artesian aquifer. Swamps developed at loci of ground-water discharge and spread across the foundering Rockdale deltaic plain (fig. 9C, Ayers and Lewis, 1985).

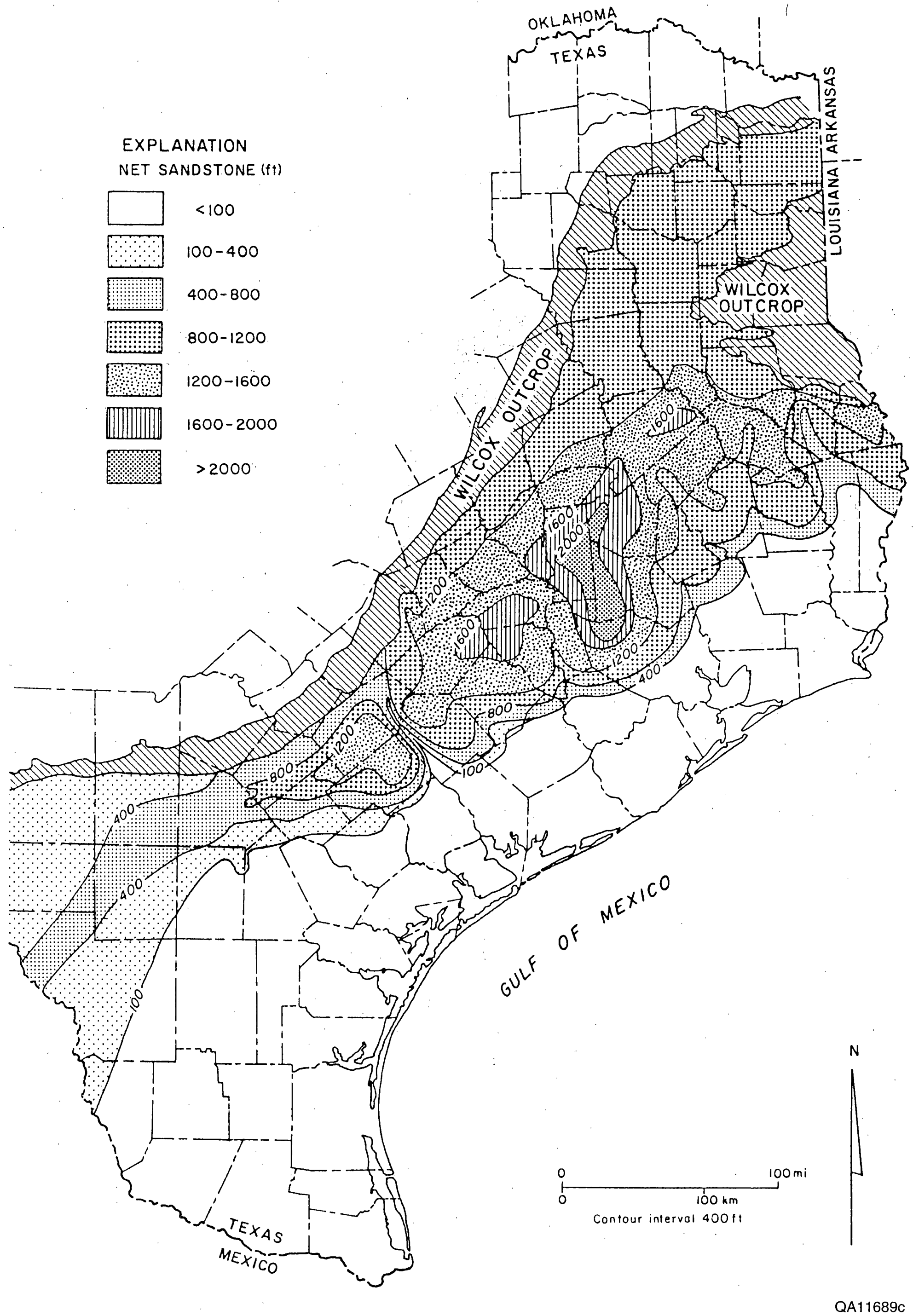


Figure 10. Net sandstone isopach map of the lower part of the Wilcox Group. Modified from Bebout and others (1982).

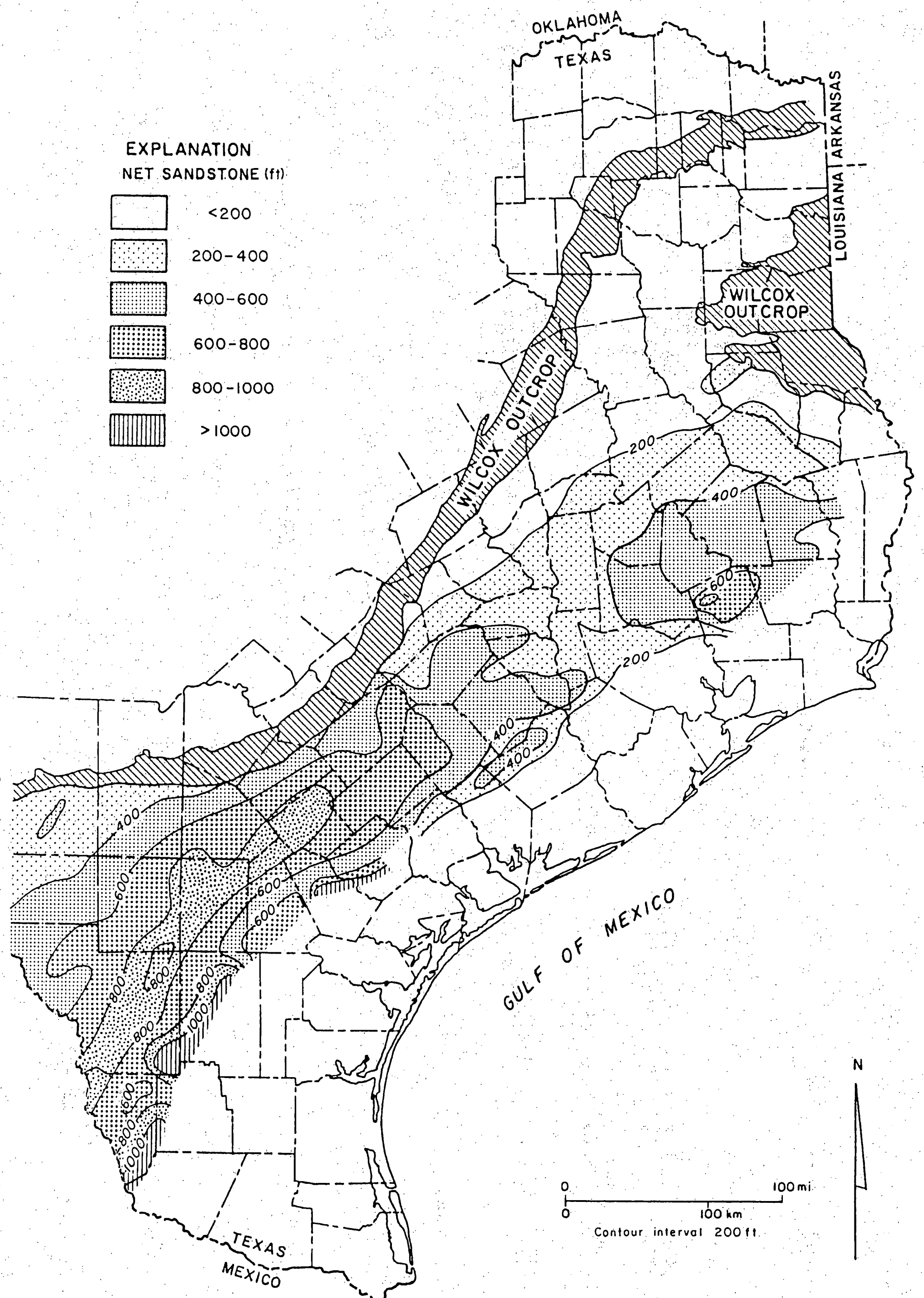


Figure 11. Net sandstone isopach map of the upper part of the Wilcox Group. Modified from Bebout and others (1982).

Evidence from lithofacies maps (Ayers and Lewis, 1985, pls. 4, 5, and 11) suggests that the Garwood subembayment existed throughout Wilcox time and was the site of frequent submarine-canyon development (Hoyt, 1959; Chuber and Begeman, 1982). Marine mud of the Sabinetown transgression in latest Wilcox time filled the Yoakum channel and, therefore, postdates canyon cutting (Hoyt, 1959); either the canyon was cut during a lowstand and was filled by the Sabinetown transgression, or it was cut during a highstand while the Rockdale fluvial system was discharging into the Garwood subembayment and was subsequently filled with mud when avulsion redirected inflow.

That the Sabinetown shale is correlatable across both the Rockdale and East Texas fluvial systems implies that the transgression results not solely from delta abandonment, as is true for local transgressions, but also from eustatic rise of sea level or major climatic changes that decreased the rate of sediment input (fig. 9D, Ayers and Lewis, 1985).

In east-central Texas, the Sabinetown transgression was terminated by Carrizo sedimentation, which was terminated by Carrizo sedimentation, which at outcrop is fluvial (aggradational) and downdip is deltaic (progradation) (fig. 9E, Ayers and Lewis, 1985). Primary influx in east-central Texas was (1) off the south flank of the Rockdale fluvial-deltaic system onto the rapidly compacting muds of the Yoakum channel and Garwood subembayment and (2) through the East Texas Basin into the Houston Embayment. The postulated wave-dominated fluvial-deltaic system that prograded through the Garwood subembayment represents the earliest evidence of significant Tertiary clastic sedimentation in the subembayment. A shift of the major axis of the Rockdale fluvial-deltaic system to the southwest left the Carrizo coastal plain to the north in Leon County foundering and forming a topographic low. Ayers and Lewis (1985) suggest that the East Texas fluvial system periodically avulsed into and aggraded that area, resulting in a reorientation of depositional trends from Wilcox to Carrizo time (fig. 9E, Ayers and Lewis, 1985).

Coal Distribution

The regional depositional settings of Wilcox coal seams were established in works by Fisher and McGowen (1967), McGowen (1968), Kaiser (1974, 1978, 1982), Kaiser and others (1978), and Ayers and Lewis (1985). The goals of the Ayers and Lewis (1985) study were (1) to refine the previously mapped depositional framework elements and coal distributions by using a larger data base and by mapping thinner stratigraphic intervals and (2) to use the new coal maps to estimate deep-basin coal resources.

Coal seams occur throughout the Wilcox stratigraphic interval, but seams are thickest and most numerous and have greatest lateral continuity in three stratigraphic zones: (1) the upper Hooper Formation, just below the Simsboro Formation; (2) the lower Calvert Bluff Formation, in a muddy interval just above the Simsboro; and (3) the upper Calvert Bluff, just below the Carrizo Sand (Ayers and Lewis, 1985). Thick coal seams are also associated with muddy intervals in the Simsboro (Ayers and Lewis, 1985), which are sandwiched between multistory, water-bearing sands.

Hooper Coal Distribution and Resources

The geometry and abundance of Hooper coal seams change in response to a change in depositional setting across a line that extends along inferred depositional strike from eastern Bastrop through central Madison County (Ayers and Lewis, 1985, pl. 23). This line is interpreted as the average position of the junction between the Hooper alluvial and deltaic plains. Updip of the line, thick (≥5 ft [1.5 m]) coal seams form discontinuous pods (Ayers and Lewis, 1985, pl. 24), and the isopleth map for all seams (Ayers and Lewis, 1985, pl. 23) shows that one to four seams occur in dip-elongate trends that coincide with log-sand, interchannel areas (floodplains) on the Hooper lithofacies map (Ayers and Lewis, 1985, pl. 4). Basinward of the line, regions of areally extensive coal seams are the rule; these tabular coal zones, which are composed of 1 to 3 thick coal seams (Ayers and Lewis, 1985, pl. 24) and 5 to 16 seams in all (Ayers and Lewis, 1985, pl. 23), coincide with high values for net major sandstones and with deltaic (distributive) sand-body geometries (Ayers and Lewis, 1985, pl. 4).

The 2,000-ft (610-m) overburden line drawn on the top of the Hooper Formation shows the downdip boundary of economic coal mining deep-basin Hooper coal, as defined in their study (Ayers and Lewis, 1985, pl. 24). The economic coal occurs in small floodplain deposits updip of the junction between the alluvial and deltaic plains, and it is most abundant on the eastern end of the region in Anderson, Freestone, and Leon Counties. Assuming a 5-ft (1.5-m) thickness for all thick coal seams and 1,750 tons (1,589 metric tons) of coal per acre-ft, 924 million tons (838 million metric tons) of coal were demonstrated between the depths of 200 and 2,000 ft (61 and 610 m).

Considerably greater Hooper coal resources (14,518 million tons [13,171 million metric tons]) are in the deltaic coal seams that lie basinward of the 2,000-ft (610-m) overburden line (Ayers and Lewis, 1985, pl. 24). Because the projected junction of the alluvial and deltaic plains approaches the outcrop in Bastrop County, Kaiser (1978) suggested exploration for thick, extensive Hooper coal seams in that region. However, coal seams are thinner and discontinuous in Bastrop and Fayette Counties (Ayers and Lewis, 1985, pl. 24) owing to pinch-out of the deltaic platform at the margin of the Garwood subembayment (Ayers and Lewis, 1985, pl. 4).

Unfavorable coalbed methane aspects for the development of upper Hooper coal in the eastern region are that (1) the overlying Simsboro is thin or muddy throughout much of the area and (2) ground-water quality of the host formation is generally poorer than water quality in the Simsboro, Calvert Bluff, and Carrizo, suggesting limited permeability.

Calvert Bluff Coal Distribution and Resources

The Calvert Bluff Formation contains more coal seams (as many as 16) (Ayers and Lewis, 1985, pl. 25) than other Wilcox formations. To better delineate the stratigraphic distribution of the coal seams, the thick (>900 ft [275 m]) Calvert Bluff Formation was divided into three intervals and the coal seams were mapped for each. Because Ayers and Lewis (1985) could not identify regional stratigraphic markers in the Calvert Bluff, the mapped intervals represent informal stratigraphic slices. The lower Calvert Bluff consists of a 300-ft (91-m) slice immediately above the Simsboro Formation, the upper Calvert Bluff extends 200 ft (61 m) below the Carrizo Sand, and the middle Calvert Bluff comprises the strata between the two.

Lower Calvert Bluff Coal

As is true for Hooper coal seams, lower Calvert Bluff coal seams are associated with fluvial-deltaic systems. Alluvial coal seams in the shallow subsurface have dip-elongate geometries (Ayers and Lewis, 1985, pls. 26 and 27) and correspond to low to intermediate Calvert Bluff sand values (Ayers and Lewis, 1985, pls. 11 and 12). Coal seams lie in interchannel (floodplain) areas and are bounded by dip-oriented, multistory channel-fill sands. Deltaic coal seams, deeper in the basin, have tabular geometries and coincide with high sand values and bifurcating (distributary) sand-body geometries.

The number of thick coal seams (Ayers and Lewis, 1985, pl. 27) correlates with the high total numbers of seams (Ayers and Lewis, 1985, pl. 26). Lower Calvert Bluff coal seams are most abundant in, and thick coal seams are almost restricted to, the area between eastern Bastrop and eastern Leon Counties (Ayers and Lewis, 1985, pls. 26 and 27), coincident with maximum development of the Simsboro. This region clearly conforms to the outline of the Rockdale fluvial-deltaic system (fig. 2; Ayers and Lewis, 1985, pl. 5). In Bastrop and Fayette Counties, coal seams (Ayers and Lewis, 1985, pl. 26) are lost as the fluvial-deltaic platform (Ayers and Lewis, 1985, pl. 12) pinches out into the Garwood subembayment. To the northeast in Leon County, the thick coal seams (Ayers and Lewis, 1985, pl. 27) terminate and the total number of coal seams (Ayers and Lewis, 1985, pl. 26) dramatically decreases at the margin of the Rockdale fluvial-deltaic system; only one or two coal seams are associated with the secondary fluvial system (described in section on "Calvert Bluff Formation") in Anderson and Houston Counties. Within the Rockdale

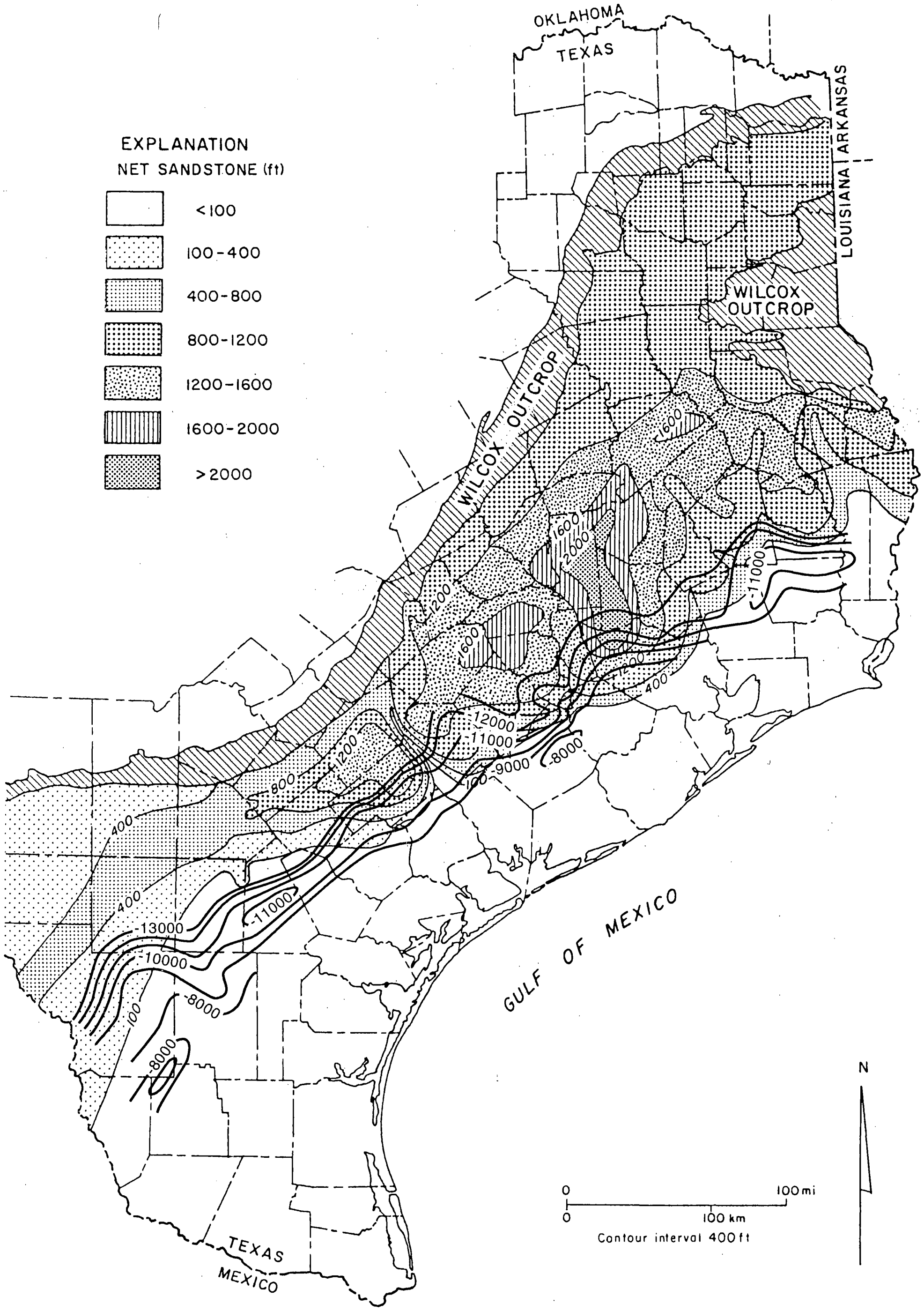


Figure 12. Depth to the operationally defined top of overpressure along the Wilcox Group trend. Modified from Bebout and others (1982).

fluvial-deltaic system, the number of thick coal seams increases basinward to more than four, and the total number of seams increases to as many as seven seams (Ayers and Lewis, 1985, pls. 26 and 27).

Lower Calvert Bluff coal seams are thickest and most abundant in a muddy interval immediately overlying, or in places stratigraphically equivalent to, the multistory, multilateral channel-fill sands of the Simsboro Formation (Ayers and Lewis, 1985). As described in the earlier sections, coal-bearing mudstones of the lower Calvert Bluff Formation cap the Simsboro Formation and punctuate a major change in the style of sedimentation. Ayers and Lewis (1985) suggested that this change is the result of diversion of the primary fluvial system from the Houston Embayment to the Rio Grande Embayment (fig. 9C; Ayers and Lewis, 1985). The abandoned Rockdale fluvial-deltaic complex provided both a platform of accumulation for lower Calvert Bluff peat (lignite) and a perennial source of water necessary to ensure persistence of the peat swamps. When coarse clastic sedimentation on the Rockdale fluvial-deltaic system ended, the sediments deposited were mostly delta-plain muds, which formed a confining layer (aquitard) over the permeable channel-fill sands of the Simsboro Formation. Thus confined, the sands of the Rockdale fluvial-deltaic complex formed a regional fresh-water aquifer having a high, stable water table. Peat swamps (lignite) developed at loci of regional ground-water discharge and spread across the abandoned delta complex.

Because the entire Calvert Bluff Formation is coal bearing, a Simsboro overburden (depth to base of Calvert Bluff) map was made by Ayers and Lewis (1985) to delineate the coal-mining exploration fairway for coal (Ayers and Lewis, 1985, pl. 28). The 2,000-ft (610-m) line from the overburden map marks the basinward boundary of potentially recoverable deep-basin coal in the lower Calvert Bluff (Ayers and Lewis, 1985, pl. 27). Landward of this line, thick interchannel coal seams (Ayers and Lewis, 1985, pl. 27) project updip to known near-surface deposits. Thick seams are most abundant between eastern Bastrop and western Leon Counties. There are 5,103 million tons (4,629 million metric tons) of deep-basin resources between 200 and 2,000 ft (61 and

610 m); three times more coal (16,150 million tons [14,651 million metric tons]) lies within the study area basinward of the 2,000-ft (610-m) line.

Favorable coalbed methane aspects for the development of lower Calvert Bluff coal seams are that (1) deep coal seams are basinward extensions of those seams currently mined at the surface; (2) generally, they are thicker and more continuous than other Wilcox coal seams in the same depth range; and (3) they are often separated from the underlying Simsboro aquifer by a low-permeability mudstone. However, the thickness of the mudstone substratum is difficult to predict, and site-specific studies would be required to assess hydrologic problems attendant with coalbed methane exploration.

Middle Calvert Bluff Coal

Geometries and depositional settings of middle Calvert Bluff coal seams are similar to those of the lower Calvert Bluff. Discontinuous, pod-shaped, and dip-elongate floodplain coal seams in the shallow subsurface give way basinward to tabular deltaic coal seams, and the total number of coal seams increases basinward to more than seven (Ayers and Lewis, 1985, pl. 29). However, middle Calvert Bluff coal seams differ markedly from lower Calvert bluff coal seams in several ways. First, it can be seen from regional cross sections (Ayers and Lewis, 1985, pls. 6 and 22) and from the comparison of coal maps (Ayers and Lewis, 1985, pls. 27 and 29) that middle Calvert Bluff coal seams are regionally less abundant and more discontinuous. Second, coal seams associated with the secondary fluvial system in Houston County are comparably more abundant in the middle Calvert Bluff than in the lower Calvert Bluff. Finally, and of most importance, the thick coal seams common to the lower Calvert Bluff are practically nonexistent in the middle Calvert Bluff. For this reason, Ayers and Lewis (1985) did not map separately the thick coal seams in this stratigraphic sequence, and they are considered poor candidates for coalbed methane resource development.

Upper Calvert Bluff Coal

Of the Wilcox coal-bearing intervals, the upper Calvert Bluff contains the least numerous and most discontinuous coal seams; they are most abundant east of the Brazos River, and, unlike other intervals, coal seams of the Rockdale fluvial-deltaic system are more abundant closer to outcrop (Ayers and Lewis, 1985, pl. 30). Ayers and Lewis (1985) attribute the paucity of deeper coal seams to progressive landward shift of depositional facies associated with the Sabinetown marine transgression. In Freestone and northern Anderson Counties the pod-shaped geometry and the distribution of coal seams relative to the Calvert Bluff framework elements (Ayers and Lewis, 1985, pl. 12) of the secondary fluvial system affirm a floodplain depositional setting. Thick coal seams (also shown on Ayers and Lewis, 1985, pl. 30) are restricted to the secondary fluvial system of the East Texas Basin. Tabular coal seams in southeastern Anderson and northwestern Houston Counties coincide with high sand values. These coal seams are attributed to peat swamps that developed during the destruction of small deltas of the secondary fluvial system. Marine shales of the Sabinetown unit overlie the abandoned deltas.

Thick Upper Calvert Bluff coal seams contain 479 million tons (434 million metric tons) of coal between 200 and 2,000 ft (61 and 610 m). There are no thick upper Calvert Bluff coal seams basinward of the 2,000-ft (610-m) line. The location of thick upper Calvert Bluff coal seams in low-sand (floodplain) areas of northern Anderson County makes them candidates for in situ gasification (Ayers and Lewis, 1985). However, attention must be given to possible hydrologic complications resulting from the proximity of the Carrizo aquifer, which overlies the coal seams. The upper Calvert Bluff coal seams are considered secondary coalbed methane targets.

Potential for East-Central Gulf Coast Basin Coalbed Methane Resource Development

In summarizing our depositional systems and coal distribution evaluation and incorporating our producibility model, the east-central Gulf Coast Basin area is located in a suitable fairway for coalbed methane resource development on the basis of its coal thickness, depth (2,000 to 6,500 ft;

610 to 1,980 m), and total reservoir interval thickness (2,000 to 3,500 ft; 610 to 1,067 m). The east-central Gulf Coast Basin's maximum coal thickness of approximately 30 ft (9.1 m) and cumulative coal thickness of as much as 100 ft (34 m) is favorable for coalbed methane resource development. The prime target for coalbed methane resource development is the lower Calvert Bluff coals. However, the continuity of the individual coal seams has not been adequately addressed. Additional reservoir characterization must be undertaken to fully evaluate the continuity of coal seams in the east-central Gulf Coast Basin area. Our experience in the Rocky Mountain Foreland suggests that the coals would be more continuous than previously mapped. However, the scope of this evaluation does not permit us to undertake this detailed evaluation.

Stratigraphic traps, including facies variation and analysis and coal seam continuity mapping, including updip pinch-outs and relief above and below sandstone bodies, must be part of the advanced reservoir characterization program. This may result in the delineation of additional conventional type traps. It is emphasized that the reservoir continuity of the sandstones should also be taken into account when evaluating the coalbed methane resources because these sandstones could also hold a significant amount of migrated gas. Importantly, the exploration program should include dually completed wells in both sandstone and coal. Updip migration of thermogenic gases and the trapping of methane in stratigraphic traps must be considered in the exploration program. If the coals become thinner in an updip direction and pinch out, then this area could become an area of potentially higher gas contents, as recorded in the San Juan and Uinta Basins.

Coal Rank and Gas Generation in East-Central Texas

Coal mining researchers have documented that shallow Tertiary coals from Texas are traditionally defined as lignite, implying that vitrinite reflectance values in east-central Texas are typically less than 0.38 percent. However, some deeper "lignites" have vitrinite reflectance values of greater than 0.38 percent, making them actually coals of subbituminous rank (vitrinite reflectance between 0.38 and 0.49 percent). From these numerous studies and publications on the thermal maturation level and chemical properties of Texas lignites (Tewalt, 1986, and Mukhopadhyay, 1989, and references therein), it is now estimated that the coal rank in the Wilcox Formation in the East-Central Texas area is generally between lignite and subbituminous, although higher rank coals are probably present in the downdip extent of the Wilcox Group. Vitrinite reflectance values for Wilcox coal samples close to outcrop, ranging from 0.30 to 0.42 percent, are supported by proximate analyses of the coal samples. However, the threshold of thermogenic gas generation in coal beds lies between 0.80 and 1 percent, indicating that the shallow coals in the study area may not have reached the thermal maturity level required to generate thermogenic gases. Moreover, Wilcox coals at depth, for example in Colorado, Dewitt, and Lavaca Counties between 9,000 and 14,000 ft (2,743 and 4,267 m), have probably reached the thermal maturity level required to generate thermogenic methane (Mukhopadhyay, 1989), and thus the potential exists for exploration of migrated thermogenic gases.

Regional geopressure and temperature trends in the Wilcox (figs. 12 and 13) indicate that the top of geopressure located south of the study area is approximately 13,000 ft (3,962 m) deep (Bebout and others, 1982). Active gas generation and hydrocarbon overpressure are thought to occur at approximately 200°F in low-permeability sediments. The 200°F temperature contour in the Wilcox is located approximately 30 mi (48 km) south of the Mexia Fault Zone, suggesting that Wilcox coals in this area may be generating thermogenic gases. Hydrocarbon overpressure has probably not developed in the shallow coal beds because of relatively high permeability of the sediments. However, the proximity of geopressure and temperatures at or above 200°F suggests the possibility of updip migration of thermogenic gases to the Mexia Fault Zone. The geometry of geopressure suggests that thermogenic gases are less likely to migrate updip in the eastern portion of the study area.

The ash content of coal beds determines the amount of gases that can be sorbed onto the coal surface. Ash content in east-central Wilcox coals is highly variable, ranging from 7.7 to 36.4 percent, with averages between 18 and 19 percent (Tewalt, 1986; Mukhopadhyay, 1989). Ash content appears to be relatively higher in deep-basin lignite compared with surface lignite.

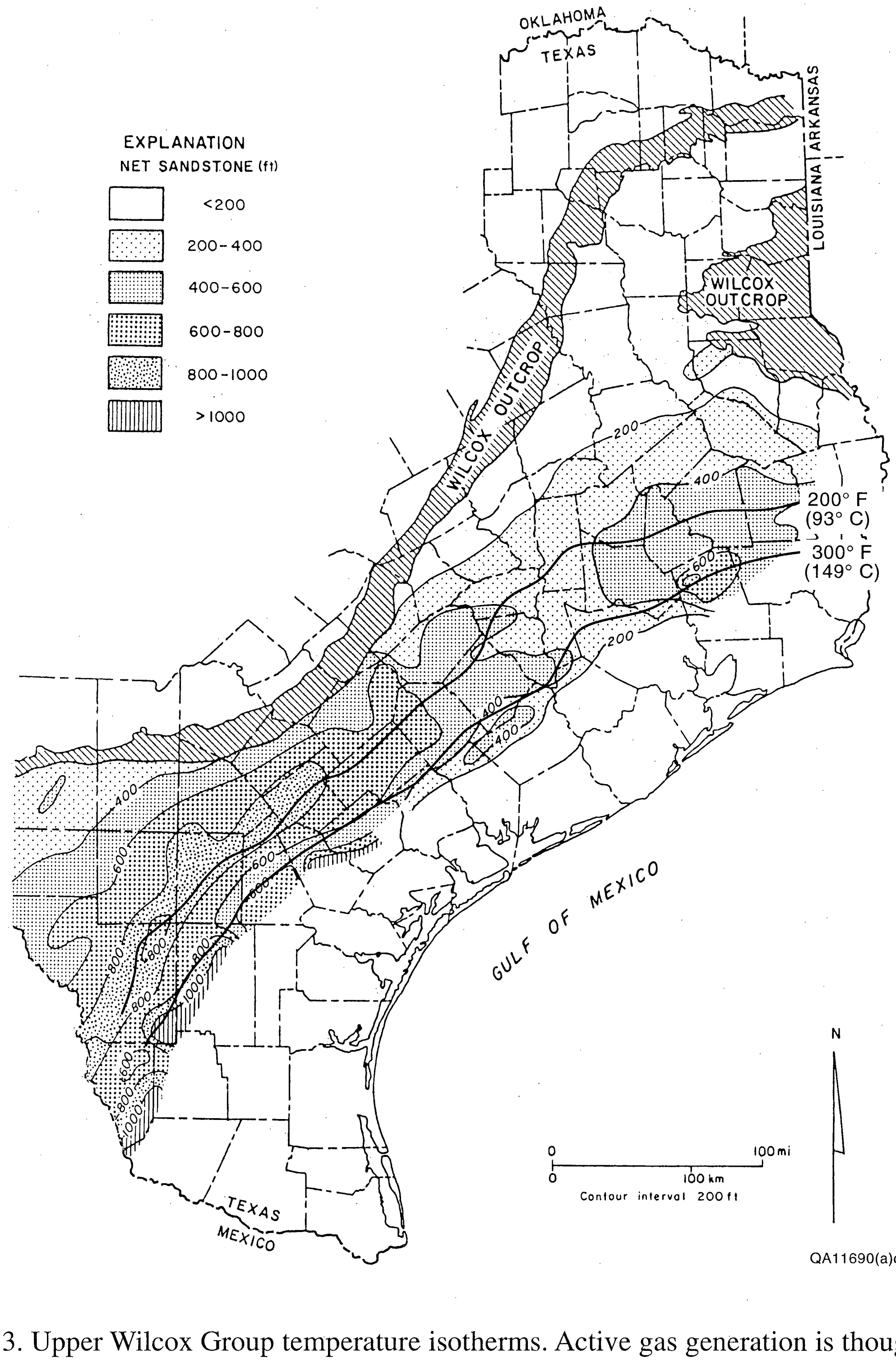


Figure 13. Upper Wilcox Group temperature isotherms. Active gas generation is thought to occur at 200°F. Modified from Bebout and others (1982).

Moreover, ash content in East Texas lignites is lower (average 11.4 percent) than in East-Central Texas lignites. Sulfur content in east-central Wilcox coals ranges from 1.07 percent in the Hooper Formation to 1.72 percent in the Upper Calvert Bluff and averages 1.43 percent in Lower Calvert Bluff coals.

Potential for Coalbed Methane Resource Development

On the basis of the limited amount of data available, it is speculated that the coal gases in the east-central Texas coal basin probably represent migrated thermogenic and secondary biogenic gases. The location of the study area is favorable for updip migration of gases that may be sorbed onto the coal surface. Secondary biogenic gases may be more common farther east, although more detailed study and data are required to determine regional hydrodynamics and particularly the geology and sealing properties in the Mexia Fault Zone.

Gas Content of Wilcox Coals in East-Central Texas

Coal gas content data are not publicly available for the east-central Texas area. Importantly, gas content is one of the more critical controls on evaluating coalbed methane potential because coalbed methane production is uneconomic if insufficient amounts of gas are sorbed onto the coal surface. A major problem in evaluating gas content trends in east-central Texas will be the accuracy of the data collected. Analytical gas content data collected can be affected by analytical method, sample type, and gas composition used during the experiments, and it is cautioned that the correct sampling methods must be applied. Assuming that the gas content data measured are reasonably accurate, there are many geologic and hydrologic factors that affect the distribution of coalbed gas in the subsurface, and these factors can be divided into three categories: (1) gas generation, (2) coal properties, and (3) reservoir conditions. Each of these factors must be taken into consideration when evaluating gas content data. Further, gas content is not fixed but changes when equilibrium conditions in the reservoir change. Therefore, the lateral and vertical distribution of gas contents is usually highly variable and will be difficult to predict, and it is recommended that a detailed stratigraphic and hydrologic evaluation be undertaken with the acquisition of gas content data.

Potential for Coalbed Methane Resource Development

Before any fairway delineation can be resolved, gas content data must be collected in the study area. The presence of high gas content values in such low-rank coals would suggest updip migration of thermogenic gases or, possibly, migration and/or in situ generation of secondary biogenic methane. Sorption isotherms can then be used to determine whether the coals are undersaturated, saturated, or oversaturated with respect to methane.

Permeability of the Wilcox Group, East-Central Texas

Previous research in bituminous coals in the Western United States has indicated that coal beds are often orders of magnitude more permeable than the surrounding sediment and, therefore, can be major aquifers in the basin. In coal beds in east-central Texas, fractures (cleats) are the permeability pathways for the flow of fluid and hydrocarbons (water and gas) to the wellbore. Permeability in coal beds is restricted to face and butt cleats (fractures) because the organic coal matrix is impermeable. Face cleats are more continuous and, therefore, usually more permeable than the associated butt cleats, and their occurrence and orientation must be evaluated. Moreover, the current direction of in situ stresses relative to face cleat orientation may also affect permeability, because permeability can be reduced when in situ stresses are perpendicular to fact cleat orientation.

With the acquisition of cleat and in situ data, understanding coal permeability in east-central Texas will be critical for determining the ultimate recovery of coalbed methane from the coal reservoir (fig. 14). A permeability of approximately 1 md represents a recovery efficiency of less than 20 percent whereas recovery factors approaching 100 percent are not achieved unless permeability values are hundreds of millidarcys. However, exceptionally high permeability may be

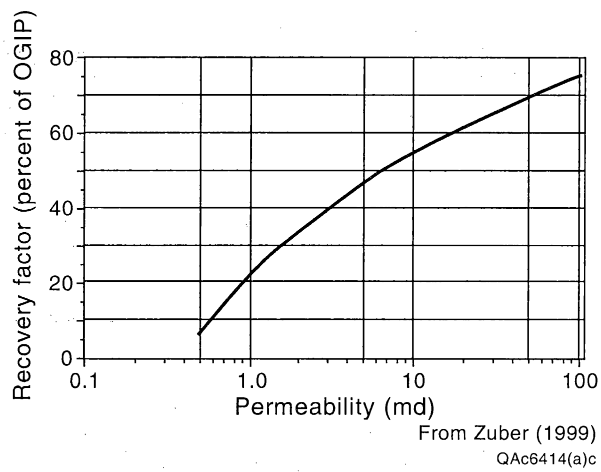


Figure 14. Relationship between permeability and recovery efficiency in coal beds. Based on data presented by M. Zuber, Holditch and Associates, Baton Rouge, Louisiana.

as detrimental to coalbed methane recovery as low permeability, because of excessive water production.

Permeability calculated from two Wilcox coal beds, located at depths of 400 to 690 ft (122 to 210 m) in the Sabine Uplift, to the east of the current study area, ranges between 22 and 99 md (Fogg, 1986; Kaiser and others, 1986). These values are an order of magnitude lower than permeabilities in low-rank coals in the Powder River Basin (1,000 md). These permeability ranges are within the permeability values associated with higher coalbed methane producibility in the San Juan and Black Warrior Basins (fig. 15). Although these values are encouraging, permeability will decrease with increasing burial depth, and the permeability of coal beds in east-central Texas at depth remains uncertain.

Average permeability in Wilcox sandstones ranges from 0.4 to 4.2 md, suggesting that the sandstones may be an order of magnitude less permeable than the coal beds. The hydraulic conductivities of interconnected channel-fill sands (framework facies) are significantly greater than conductivities of interchannel areas (nonframework facies) (Fogg and others, 1983a). Additionally, permeabilities of channel-fill sandstones may increase with sand-unit thickness (Payne, 1968, 1975). Permeability values for well-connected fluvial sandstone channels range from 0.4 to 3.7 md, whereas permeability in less well connected sandstone ranges from 0.004 to 0.4 md. Because permeability decreases away from channel sandstones toward channel margins and floodplain sediments (including coal beds deposited adjacent to fluvial channels), the associated coals may not be in hydraulic continuity with adjacent sandstones. Additional permeability data need to be acquired before any predictions of the coalbed methane potential can be evaluated.

Hydrogeology of the Wilcox Group, East-Central Texas

Hydrogeology is one of the more important factors affecting coalbed methane producibility and includes both ground-water flow from the outcrop basinward, and updip migration of fluids

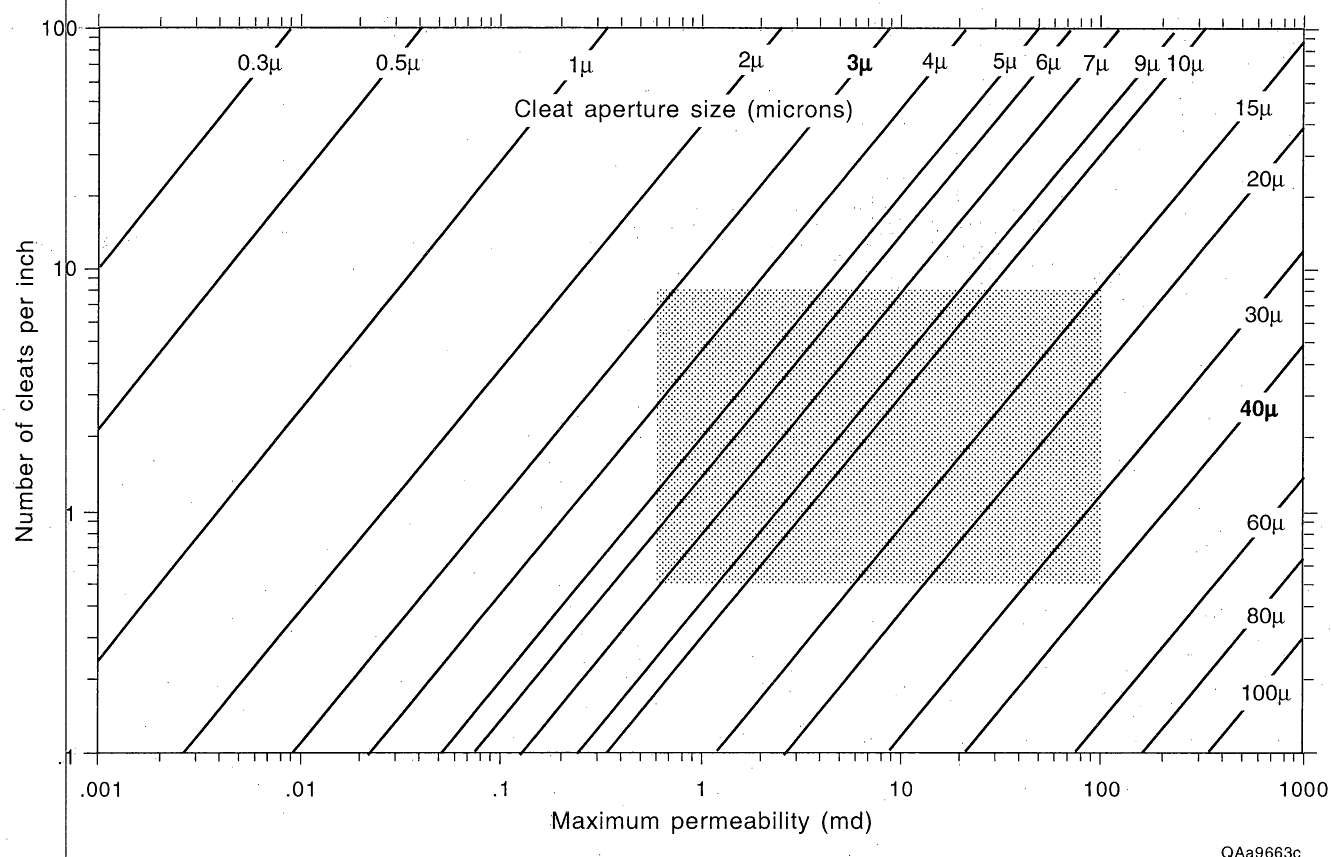


Figure 15. Range of permeabilities in highly productive coal beds. This graph shows the relationship among permeability, cleat frequency, and cleat aperture based on a cubic law equation that is normally applied to fractured carbonate reservoirs. Although permeability within coal beds ranges from less than 0.001 to more than 1,000 plus md, permeability in coal beds from the San Juan and Black Warrior Basins generally ranges from approximately 0.5 to 100 md. Modified from Scott (1999).

(water and hydrocarbons). Understanding the geometry of hydrodynamics is critical in delineating area of upward flow potential and, therefore, areas of potentially better coalbed methane producibility. Potentiometric surface, geochemical, and ground-water resistivity maps of the major units were used to evaluate regional flow directions from the outcrop and possible subsurface recharge in the Carrizo Sandstone in the Leon and Freestone Counties.

Thick, interconnected Wilcox sands are more permeable than thinner sands and muds of the surrounding interchannel areas (nonframework facies), indicating that channel-fill sands serve as conduits for ground-water flow (Payne, 1968, 1975; Fogg and others, 1983b; Ayers and others, 1984). Therefore, the stratigraphic framework facies tend to have higher resistivities than the adjacent, nonframework facies in the shallow subsurface (Payne, 1968, 1975).

These observations, together with the basinward distribution of fresh-water lobes coincident with channel-sand axes, indicate that the framework facies strongly control ground-water flow. Resistivity maps (Ayers and Lewis, 1985, pls. 18 and 19) delineate recharge areas and elucidate ground-water flowpaths, thus serving as additional tools for understanding the hydrodynamics of the area. Note, however, that formation resistivity may be affected by factors other than salinity of the formation water (for example, clay content of the sand or presence of hydrocarbons). Salinity deeper in the basin ranges from 60,000 to 119,000 ppm in Colorado County (Bebout and others, 1982).

The basinward limit of meteoric recharge was placed at 20 ohm-m^2/m (Ayers and Lewis, 1985; Kaiser and others, 1986) on the resistivity of the maximum sands. Wilcox coals appear to thin northward toward the recharge area, suggesting that meteoric recharge may be focused in fluvial sandstone rather than in coals. The serrated distribution of higher resistivity values (that is, relatively fresh water) in the Simsboro, Calvert Bluff, and Carrizo Formations, indicates that sandstone geometry controls the downdip migration and extent of fresh meteoric water. Resistivity maps by Ayers and Lewis (1985, pls. 18 and 19) of the Calvert Bluff and Carrizo Formations indicate that the Mexia Fault Zone at least partially inhibits the basinward migration of fresh water in Bastrop County.

The basinward limits of meteoric recharge for the Carrizo, Calvert Bluff, and Simsboro sandstones generally correspond to a zone located south of the Mexia Fault Zone, roughly paralleling a line between Giddings and Bryan. However, recharge in the Carrizo Sandstone in Madison, Houston, and Trinity Counties extends much farther into the basin than recharge for the Calvert Bluff and Simsboro. Meteoric recharge in Lee and Brazos Counties may be partially inhibited by the presence of geopressure and/or higher temperatures (figs. 12 and 13) located southward of the study area. This area of overpressure is much closer to the outcrop belt compared with the distribution of overpressure farther east. Meteoric recharge immediately north of the Mexia Fault Zone in eastern Milam County (Kaiser and others, 1986) is directed away from the basin, indicating that piracy of recharge may partially limit the amount of meteoric water entering the coal-bearing units. Another area of ground-water piracy occurs in eastern Falls County.

Updip migration of thermogenic gases to Wilcox coal beds is favored in this area because of the distribution of regional geopressure and high temperatures (more than 200°F) and recharge piracy. Additionally, at least some thicker coals in the basin pinch out toward the outcrop, suggesting that (1) the coals may be separated laterally from aquifer sandstones by lower permeability mudstones and, therefore, may not be in hydraulic communication with the sands, and (2) coals thinning toward the outcrop may have a lower probability of being recharged by ground water. A more detailed structural and stratigraphic evaluation is required to assess the sealing properties of the Mexia Fault Zone and the ways the faults may affect the downward and upward migration and trapping of fluids. Although updip migration is favored, at least some recharge probably does occur in thicker coal beds located near the outcrop, and an east-central Texas exploration and development program could invoke a combination of migrated thermogenic gases and secondary biogenic gases.

CONCLUSIONS

The objective of this cooperative agreement between the Bureau of Economic Geology (BEG), The University of Texas at Austin, and the U.S. Geological Survey (USGS) is to provide a preliminary assessment of the coalbed methane potential of the east-central Texas Gulf Coast coal basins based on previously published literature.[†] Because of the limited scope of this project, a detailed evaluation of the area was not performed and areas of higher coalbed methane potential were not delineated. The following discussion summarizes the positive and negative attributes of the area on the basis of a BEG coalbed methane producibility model. A more detailed evaluation that includes advanced reservoir characterization and engineering modeling, and that incorporates key geologic and engineering attributes, is recommended to fully assess the economic viability of the project (Appendix A).

The east-central Texas coal basin occurs dowdip from a major faulted graben (Mexia Fault Zone) that potentially may act as the permeability barrier to fluid flow in the updip (gas) and/or downdip (water and secondary biogenic gas) direction. The east-central Texas coal basin lies updip of the Stuart City shelf margin, suggesting that the Wilcox Group, the prime target for coalbed methane resource development, was not significantly affected by major growth faults, although syndepositional and postdepositional faulting are recognized in the Wilcox Group and Carrizo Sands. The Wilcox is, however, more steeply dipping in Lee, Fayette, and Bastrop Counties than in counties located to the northeast. Subtle structural control of fluvial-deltaic trends is inferred from isopach maps, sandstone geometry, and considerable postdepositional faulting, with more than 800 ft (244 m) of vertical displacement occuring in Lee, Burleson, Milam, and Robertson Counties. This fault system may have important implications for basinward movement of ground water and updip trapping of fluids including migrated thermogenic gases.

[†]Most of the coal resource data were obtained from the Ayers and Lewis (1985) Deep-Basin Lignite Resource study, and the digital maps provided for the coalbed methane assessment are compatible with NCRDS.

Depth to the main Wilcox coal-bed producing intervals is favorable, ranging from approximately 2,000 to 6,500 ft (610 to 1,980 m). The Wilcox total thickness of between 2,000 and 3,500 ft (610 to 1,067 m) of gross section, containing multiple coal and sandstone reservoirs, is also favorable. Moreover, migration of gases from existing Wilcox gas fields close to the east-central Gulf Coast Basin is an additional favorable attribute. Therefore, gas migrating in sandstone reservoirs should also be included in the coal gas resource assessment. Natural fracture systems (coal cleat) and in situ stresses are unknown attributes in the east-central Gulf Coast Basin area. Coal cleat acts as the permeability pathway for migration of both the gas and the water to the wellbore, and coal cleat attributes and in situ stresses need to be evaluated prior to determining the permeability of the reservoir in the exploration program.

Depositionally, coal seams occur throughout the Wilcox stratigraphic interval but are thickest, most numerous, and have the greatest lateral continuity in three stratigraphic zones: (1) the upper Hooper Formation, immediately below the Simsboro sand, (2) the lower Calvert Bluff Formation, immediately above the Simsboro sand, and (3) the upper Calvert Bluff, immediately below the Carrizo Sand. Net coal maps have not been published, although maps showing the number of "thick" lignite (more than 5 ft [2 m] thick) published by Ayers and Lewis (1985) can be used to estimate a minimum net coal thickness. Regionally, net coal thickness trends in the Hooper, lower Calvert Bluff, middle Calvert Bluff, and upper Calvert Bluff appear to thin northwest toward the outcrop belt. Although coals are present at outcrop, thicker coals may be present downdip. Net coal thickness is generally greatest in sand-poor areas, although some maximum net coal thickness trends correspond to fluvial axes. Coal seams associated with the Mount Pleasant fluvial system are elongate adjacent to channel sands. Coals associated with Wilcox deltaic facies are tabular and may be restricted locally if formed in an interdistributary setting or are regionally extensive if developed across abandoned deltas. If only the thick (>5 ft [2 m]) coal seams are considered, the lower Calvert Bluff coals exceed 40 ft (12 m) in some parts of the area and are the prime target for coalbed methane resource development. Net coal thickness for the entire coal-bearing interval can exceed 100 ft (35 m) in the study area. Stratigraphic traps, including facies variation and analysis, and coal seam continuity mapping, are recommended as part of an advanced reservoir characterization program.

Coal rank in the Wilcox Formation generally ranges between lignite and subbituminous, although higher rank coals may be present downdip. Vitrinite reflectance values for Wilcox coal samples at the outcrop range from 0.30 to 0.42 percent at a depth of 2,000 ft (610 m). The threshold of thermogenic gas generation in coal beds lies between 0.80 and 1 percent, indicating that the coals in the study area have not reached the thermal maturity level required to generate thermogenic gases. Wilcox coals in Colorado, Dewitt, and Lavaca Counties at depths ranging between 9,000 and 14,000 ft (2,743 and 4,267 m), have probably reached the thermal maturity level required to generate thermogenic methane, and the potential for migrated and thermogenic gas becomes more viable. Ash content in east-central Wilcox coal beds is highly variable, ranging from 7.7 to 36.4 percent and averaging 18.3 percent. Ash content appears to be relatively higher in deep-basin lignites compared with surface lignites. Sulfur content in east-central Wilcox coals ranges from 1.07 percent in the Hooper Formation to 1.72 percent in the Upper Calvert Bluff and averages 1.43 percent in Lower Calvert Bluff coals.

To date, gas content values are not publicly available in the study area. If limited gas content data were available, access to these data can be invaluable because critical information regarding fluid migration and the economic viability of the project could be evaluated. However, high gas content values in such low-rank coals would be encouraging and would suggest updip migration of thermogenic gases or, possibly, migration and/or in situ generation of secondary biogenic methane. Sorption isotherms are also not available, making it impossible to evaluate whether the coals are undersaturated, saturated, or oversaturated with respect to methane.

Previous hydrologic research in bituminous coals in the Western United States has indicated that coal beds are often orders of magnitude more permeable than the surrounding sediment. Permeability calculated from two Wilcox coal beds at depths of 400 to 690 ft (122 to 210 m) in the Sabine Uplift ranges between 22 and 99 md, which is an order of magnitude lower than permeabilities in low-rank coals in the Powder River Basin. Although these values are encouraging, permeability will decrease with increasing burial depth, and the permeability of coal at depth remains uncertain. The average permeability in Wilcox sandstones ranges between 0.4 and 4.2 md. Permeability values for well-connected fluvial sandstone channels range between 0.4 and 3.7 md, whereas permeability in less well connected sandstone ranges between 0.004 and 0.4 md. Permeability decreases away from channel sandstones toward channel margins and floodplain sediments including coal beds deposited adjacent to fluvial channels.

Hydrodynamically, the regional migration of fluids in the Wilcox Group represents a balance among downward migration of meteoric water, resulting in the possible generation of secondary biogenic gases and updip migration of thermogenic gases. Higher gas contents in these lower rank coals located south of the Mexia Fault Zone would represent either updip migration of thermogenic gases or the generation of secondary biogenic gases. The distribution of regional overpressure trends and formation temperatures for the middle Wilcox suggest that updip migration of fluids could be favored in this area. However, coal gases located in the eastern part of the east-central Texas Gulf Coast coals probably have a larger secondary biogenic component, although updip migration of thermogenic gases is possible as well. There is not enough information to determine whether the coal beds are hydraulically connected with the sandstone aquifers. Coal beds in the Sabine Uplift area can either remain isolated from the aquifer system or be hydraulically connected with the sandstones.

Wilcox coals appear to thin northward toward the recharge area, suggesting that meteoric recharge may be focused in fluvial sandstone rather than in coals. The distribution of higher resistivity values (that is, relatively fresh water) in the Simsboro, Calvert Bluff, and Carrizo Formations suggests that sandstone geometry controls the downdip migration and extent of fresh meteoric water. Resistivity maps of the Calvert Bluff and Carrizo Formations indicate that the Mexia Fault Zone at least partially inhibits the basinward migration of fresh water in Bastrop County. Potentiometric surface maps of the outcrop area suggest that recharge is directed away from the basin immediately north of the study area. A more detailed structural and stratigraphic evaluation is required to assess the sealing properties of the Mexia Fault Zone and the ways the faults may affect the downward and upward migration and trapping of fluids.

In summary, the east-central Texas Gulf Coast Basin area is located in a suitable fairway for coalbed methane resource development on the basis of coal thickness, depth, and total reservoir interval thickness. The east-central Texas coal basin maximum coal thickness of 30 ft (9 m) and cumulative coal thickness of as much as 100 ft (35 m) are favorable for coalbed methane resource development. However, the continuity of the individual coal seams has not been adequately studied. Evaluation of stratigraphic traps, including facies variation and analysis, and coal seam continuity mapping, above and below sandstone partings, must be part of the advanced reservoir characterization program. Updip migration of thermogenic gases, generation of secondary biogenic gases, and conventional trapping of methane in structural and stratigraphic traps must be considered and evaluated in the advanced exploration program.

ACKNOWLEDGMENTS

This research was funded by the U.S. Geologic Survey under cooperative agreement no. 99HQAG0018. The Ayers and Lewis (1985) study was funded by the Texas Energy and Natural Resources Advisory Council under contract number IAC(82-83)-0822 and by special appropriation from the Texas Legislature. The computing staff of the Bureau of Economic Geology provided guidance in data processing and computer-assisted mapping. Drafting was by the Computer Graphics staff of the Bureau under the direction of Joel L. Lardon. Word processing was by Susan Lloyd, and editing was by Susann Doenges.

BIBLIOGRAPHY

Ayers, W. B., Jr., 1984, Depositional systems and coal occurrence in the Fort Union Formation (Paleocene), Powder River Basin, Wyoming and Montana: The University of Texas at Austin, Ph.D. dissertation, 208 p.

Ayers, W. B., and Lewis, A. H., 1985, The Wilcox Group and Carrizo Sand (Paleogene) in east-central Texas: depositional systems and deep-basin lignite: The University of Texas at Austin, Bureau of Economic Geology, 19 p., 30 pls.

Ayers, W. B., Jr., and Kaiser, W. R., eds., 1994, Coalbed methane in the Upper Cretaceous Fruitland Formation, San Juan Basin, New Mexico and Colorado: The University of Texas at Austin, Bureau of Economic Geology, Report of Investigations No. 218, Colorado Geologic Survey, Department of Natural Resources, Resource Series 31, and New Mexico Bureau of Mines and Mineral Resources Bulletin 146, 216 p.

Ayers, W. B., Jr., Kaiser, W. R., and Levine, J. R., 1992, Coalbed methane: depositional, hydrologic, and petrologic controls on reservoir characteristics of coal beds: American Association of Petroleum Geologists Energy Minerals Division, Short Course No. 13, 226 p.

Ayers, W. B., Jr., Kaiser, W. R., Laubach, S. E., Ambrose, W. A., Baumgardner, R. W., Jr., Scott, A. R., Tyler, Roger, Yeh, Joseph, Hawkins, G. J., Swartz, T. E., Schultz-Ela, D. D., Zellers, S. D., Tremain, C. M, and Whitehead, N. H., III, 1991, Geologic and hydrologic controls on the occurrence and producibility of coalbed methane, Fruitland Formation, San Juan Basin: The University of Texas at Austin, Bureau of Economic Geology, topical report prepared for the Gas Research Institute under contract no. 5087-214-1544 (GRI-91/0072), 314 p.

Ayers, W. B., Jr., Lewis, A. H., and Collins, G. F., 1984, Resistivity, lignite, and lithofacies mapping of the Wilcox Group, east-central Texas, *in* Kaiser, W. R., and others, Evaluating the geology and ground-water hydrology of deep-basin lignite in the Wilcox Group of East Texas: The University of Texas at Austin, Bureau of Economic Geology, final report prepared for Texas Energy and Natural Resources Advisory Council under contract no. IAC (82-83)-0822, p. 44–70.

Bammel, B. H., 1979, Stratigraphy of the Simsboro Formation, east-central Texas: Baylor Geological Studies Bulletin No. 27, 39 p.

Barnes, V. E., 1967, Palestine sheet: The University of Texas at Austin, Bureau of Economic Geology, Geologic Atlas of Texas, scale 1:250,000.

Barnes, V. E., 1970, Waco sheet: The University of Texas at Austin, Bureau of Economic Geology, Geological Atlas of Texas, scale 1:250,000.

Barnes, V. E., 1979, Seguin sheet: The University of Texas at Austin, Bureau of Economic Geology, Geologic Atlas of Texas, scale 1:250,000.

Barnes, V. E., 1981, Austin sheet: The University of Texas at Austin, Bureau of Economic Geology, Geologic Atlas of Texas, scale 1:250,000.

Bebout, D. G., Weise, B. R., Gregory, A. R., and Edwards, M. B., 1982, Wilcox sandstone reservoirs in the deep subsurface along the Texas Gulf Coast: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 117, 125 p.

Chapin, C. E., and Cather, S. M., 1981, Eocene tectonics and sedimentation in the Colorado Plateau – Rocky Mountain area, *in* Dickinson, W. R., and Payne, W. D., eds., Relations of tectonics to ore deposits in the southern Cordillera: Arizona Geological Society Digest, v. 14, p. 173–198.

Chuber, Stewart, and Begeman, R. L., 1982, Productive lower Wilcox stratigraphic traps from an entrenched valley in Kinkler field, Lavaca County, Texas: Gulf Coast Association of Geological Societies Transactions, v. 32, p. 255–262.

Culbertson, J. A., 1940, Downdip Wilcox (Eocene) of coastal Texas and Louisiana: American Association of Petroleum Geologists Bulletin, v. 24, no. 11, p. 1891–1922.

Dunbar, C. O., and Rodgers, John, 1957, Principles of stratigraphy: New York, John Wiley, 356 p.

Dutton, A. R., 1999, Groundwater availability in the Carrizo-Wilcox aquifer in Central Texas—numerical simulation of 2000 through 2050 withhdrawal projections: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 256, 53 p.

Echols, D. J., and Malkin, D. S., 1948, Wilcox (Eocene) stratigraphy, a key to production: American Association of Petroleum Geologists Bulletin, v. 32, no. 1, p. 11–33.

Echols, J. B., 1995, Coalbed methane: a production energy source in the Paleocene-Eocene Wilcox of central Louisiana and southwest Mississippi: Louisiana State University, Basin Research Institute Bulletin, v. 5, p. 3–6.

Edwards, M. B., 1981, Upper Wilcox Rosita delta system of South Texas: growth-faulted shelf-edge deltas: American Association of Petroleum Geologists Bulletin, v. 65, no. 1, p. 54–73.

Fisher, W. L., and McGowen, J. H., 1967, Depositional systems in the Wilcox Group of Texas and their relationship to the occurrence of oil and gas: Gulf Coast Association of Geological Societies Transactions, v. 17, p. 105–125.

Fogg, G. E., 1980, Salinity of formation waters, *in* Kreitler, C. W., and others, Geology and geohydrology of the East Texas Basin, a report on the progress of nuclear waste isolation feasibility studies (1979): The University of Texas at Austin, Bureau of Economic Geology Geological Circular 80-12, p. 68–72.

Fogg, G. E., 1986, Groundwater flow and sandbody interconnectedness on a thick, multiple-aquifer system: Water Resources Research, v. 22, no. 5, p. 679–694.

Fogg, G. E., Kaiser, W. R., Ambrose, M. L., and Macpherson, G. L., 1983a, Regional aquifer characterization or deep-basin lignite mining, Sabine Uplift area, northeast Texas: The University of Texas at Austin, Bureau of Economic Geology Geological Circular 83-3, 30 p.

Fogg, G. E., Seni, S. J., and Kreitler, C. W., 1983b, Three-dimensional ground-water modeling in depositional systems, Wilcox Group, Oakwood salt dome area, East Texas: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 133, 55 p.

Galloway, W. E., 1968, Depositional history of the Wilcox Group, east-central Louisiana: The University of Texas at Austin, Master's thesis, 86 p.

Hoyt, W. V., 1959, Erosional channel in the middle Wilcox near Yoakum, Lavaca County, Texas: Gulf Coast Association of Geological Societies Transactions, v. 9, p. 41–50.

Jackson, M. P. A., 1981, Tectonic environment during early infilling of the East Texas Basin, *in* Kreitler, C. W., and others, Geology and geohydrology of the East Texas Basin, a report on the progress of nuclear waste isolation feasibility studies (1980): The University of Texas at Austin, Bureau of Economic Geology Geological Circular 81-7, p. 7–11.

Jackson, M. P. A., 1982, Fault tectonics of the East Texas Basin: The University of Texas at Austin, Bureau of Economic Geology Geological Circular 82-4, 31 p.

Kaiser, W. R., 1974, Texas lignite: near-surface and deep-basin resources: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations, No. 79, 70 p.

Kaiser, W. R., 1978, Depositional systems in the Wilcox Group (Eocene) of east-central Texas and the occurrence of lignite, *in* Kaiser, W. R., ed., Proceedings, 1976 Gulf Coast Lignite Conference: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 90, p. 33–53.

Kaiser, W. R., 1982, Lignite depositional models, Texas Eocene: a regional approach to coal geology, *in* Shobert, H. H., ed., Proceedings of the Basic Coal Science Workshop, Houston, Texas, 1981: U.S. Department of Energy, Grand Forks Technology Center, p. 9-67.

Kaiser, W. R., 1986, Geology and ground-water hydrology of deep-basin lignite in the Wilcox Group of East Texas: a summary, *in* Kaiser, W. R., and others, Geology and ground-water hydrology of deep-basin lignite in the Wilcox Group of East Texas: The University of Texas at Austin, Bureau of Economic Geology Special Publication, p. 3–11.

Kaiser, W. R., 1992, Coalbed methane in the Greater Green River Basin, Wyoming and Colorado, in Greater Green River Basin natural gas technology workshop: Gas Research Institute, U.S. Department of Energy, and Independent Petroleum Association of Mountain States, p. 87–114.

Kaiser, W. R., 1994, Development and evaluation of a basin-scale coalbed methane producibility model: In Focus-Tight Gas Sands, v. 10, no. 1, p. 47–52.

Kaiser, W. R., Ambrose, M. L., Ayers, W. B., Jr., Blanchard, P. E., Collins, G. F., Fogg, G. E., Gower, D. L., Ho, C. L., Holland, C. S., Jackson, M. L. W., Jones, C. M., Lewis, A. H., Macpherson, G. L., Mahan, C. A., Mullin, A. H., Prouty, D. A., Tewalt, S. J., and Tweedy, S. W., Geology and ground-water hydrology of deep-basin lignite in the Wilcox Group of East Texas: The University of Texas at Austin, Bureau of Economic Geology, 182 p.

Kaiser, W. R., and Ayers, W. B., Jr., 1994, Geologic and hydrologic characterization of coalbed-methane reservoirs in the San Juan Basin: SPE Formation Evaluation, v. 9, no. 3, p. 175-184.

Kaiser, W. R., Ayers, W. B., Jr., and LaBrie, L. W., 1980, Lignite resources in Texas: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 104, 52 p.

Kaiser, W. R., Hamilton, D. S., Scott, A. R., and Tyler, Roger, 1993a, Predicting the producibility of coalbed methane: an example from the Rocky Mountain Foreland: Geological Society of America Abstracts with Programs, v. 25, no. 6, p. A-301.

Kaiser, W. R., Hamilton, D. S., Scott, A. R., and Tyler, Roger, 1994a, A basin-scale coalbed methane producibility model: comparison of the San Juan and Sand Wash Basins (abs.): American Association of Petroleum Geologists, Annual Convention official program, v. 3, p. 182–183.

Kaiser, W. R., Hamilton, D. S., Scott, A. R., and Tyler, Roger, 1994b, Geological and hydrological controls on the producibility of coalbed methane: Journal of the Geological Society, v. 151, p. 417–420.

Kaiser, W. R., Johnston, J. E., and Bach, W. N., 1978, Sand-body geometry and the occurrence of lignite in the Eocene of Texas: The University of Texas at Austin, Bureau of Economic Geology Geological Circular 78-4, 19 p.

Kaiser, W. R., Scott A. R., Hamilton D. S., and Tyler Roger, 1995a, Evolution of a basin-scale coal-gas producibility model: geology and hydrogeology of coal bed methane producibility in the United States: analogs for the world: Intergas Unconventional Gas Symposium, May 15–16, Tuscaloosa, Alabama, p. 317–328.

Kaiser, W. R., Scott, A. R., Hamilton, D. S., Tyler, Roger, McMurry, R. G., Zhou, Naijiang, and Tremain, C. M., 1993b, Geologic and hydrologic controls on coalbed methane: Sand Wash Basin, Colorado and Wyoming: The University of Texas at Austin, Bureau of Economic Geology topical report prepared for the Gas Research Institute under contract no. 5091-214-2261 (GRI-92/0420), 151 p.

Kaiser, W. R., Scott, A. R., Hamilton, D. S., Tyler, Roger, McMurry, R. G., Zhou, Naijiang, and Tremain, C. M., 1994c, Geologic and hydrologic controls on coalbed methane: Sand Wash Basin, Colorado and Wyoming: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 220, and Colorado Geologic Survey, Department of Natural Resources, Resource Series 30, 151 p.

Kaiser, W. R., Scott, A. R., Tyler, Roger, 1995b, Geology and hydrogeology of coal bed methane producibility in the United States: analogs for the world: Intergas Unconventional Gas Symposium, May 15–16, Tuscaloosa, Alabama, 515 p.

Kohls, D. W., 1967, Petrology of the Simsboro Formation of northeast Texas: Journal of Sedimentary Petrology, v. 37, no. 1, p. 184–204.

Lower Colorado River Authority, 1984, LCRA and lignite: Lower Colorado River Authority, Lower Colorado River Review, v. 9, no. 1, p. 2–8.

McGowen, J. H., 1968, Utilization of depositional models in exploration for nonmetallic minerals, *in* Brown, L. F., Jr., ed., Proceedings, Fourth Forum on Geology of Industrial Minerals: The University of Texas at Austin, Bureau of Economic Geology, p. 157–174.

McGowen, J. H., and Garner, L. E., 1970, Physiographic features and stratification types of coarse-grained point bars, modern and ancient examples: Sedimentology, v. 14, p. 77–111.

McMurry, R. G., and Tyler, Roger, 1996, Genetic stratigraphy and coal deposition of progradational sequences in the Upper Cretaceous Williams Fork Formation, Mesaverde Group, Piceance Basin, Colorado, *in* Tyler, Roger, Scott, A. R., Kaiser, W. R., Nance, H. S., McMurry, R. G., Tremain, C. M., and Mavor, M. J., Geologic and hydrologic controls critical to coalbed methane producibility and resource assessment: Williams Fork Formation, Piceance Basin, Northwest Colorado: topical report prepared for the Gas Research Institute under contract no. 5091-214-2261.

Mukhopadhyay, P. K., 1989, Organic petrography and organic geochemistry of Texas Tertiary coals in relation to depositional environment and hydrocarbon generation: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 188, 118 p.

Payne, J. N., 1968, Hydrologic significance of the lithofacies of the Sparta Sand in Arkansas, Louisiana, Mississippi, and Texas: U.S. Geological Survey Professional paper 569-A, 17 p.

Payne, J. N., 1975, Geohydrologic significance of lithofacies of the Carrizo Sand of Arkansas, Louisiana, and Texas and Meridian Sand of Mississippi: U.S. Geological Survey Professional Paper 569-D, 11 p.

Plummer, F. B., 1932, Cenozoic systems in Texas, *in* Sellards, E. H., Adkins, W. S., and Plummer, F. B., The geology of Texas, vol. 1, stratigraphy: University of Texas, Austin, Bureau of Economic Geology Bulletin 3232, p. 519–818.

Scott, A. R., 1993, Composition and origin of coalbed gases from selected basins in the United States, *in* Thompson, D. A., ed., Proceedings from the 1993 International Coalbed Methane Symposium, Birmingham, Alabama, May 17- 24, 1993, Paper 9370, Vol. I, p. 207–222.

Scott, A. R., 1994a, Coalbed gas composition, Upper Cretaceous Fruitland Formation, San Juan Basin, Colorado and New Mexico: Colorado Geologic Survey Open File Report 94-2, 28 p.

Scott, A. R., 1994b, Composition of coalbed gases: In Situ, v. 18, no. 2, p. 185–208.

Scott, A.R., 1995, Limitations and benefits of microbially enhanced coal bed methane: Intergas Unconventional Gas Symposium, May 14–20, Tuscaloosa, Alabama, p. 423–432.

Scott, A. R., 1996, Coalification, cleat development, coal composition and origins, and gas content of Williams Fork coals in the Piceance Basin, Colorado, *in* Tyler, Roger, Scott, A. R., Kaiser, W. R., Nance, H. S., McMurry, R. G., Tremain, C. M., and Mavor, M. J., Geologic and hydrologic controls critical to coalbed methane producibility and resource assessment: Williams Fork Formation, Piceance Basin, Northwest Colorado: topical report prepared for the Gas Research Institute under contract no. 5091-214-2261, p. 220–251.

Scott, A. R., 1999, Improving coal gas recovery with microbially enhanced coalbed methane, *in* Mastalerz, Maria, Glikson, Miryam, and Golding, S. D., eds., Coalbed methane scientific, environmental and economic evaluation: Kluwer Academic Publishing, p. 89–110.

Scott, A. R., and Ambrose, W. A., 1992, Thermal maturity and coalbed methane potential of the Greater Green River, Piceance, Powder River, and Raton Basins (abs.): American Association of Petroleum Geologists annual convention official program, p. 116.

Scott, A. R., and Kaiser, W. R., 1994, On the geomechanics of open-hole cavity completions in San Juan Basin coalbed gas wells (extended abs.), *in* The First North American Rock Mechanics Symposium poster sessions abstracts: International Society for Rock Mechanics, p. 63–66.

Scott, A. R., Kaiser, W. R., and Ayers, W. B., Jr., 1991, Composition, distribution, and origin of Fruitland Formation and Pictured Cliffs Sandstone gases, San Juan Basin, Colorado and New Mexico, *in* Schwochow, S. D., Murray, D. K., and Fahy, M. F., eds., Coalbed methane of western North America: Rocky Mountain Association of Geologists, guidebook for the Rocky Mountain Association of Geologists Fall Conference and Field Trip, p. 93–108.

Scott, A. R., Kaiser, W. R., and Ayers, W. B., Jr., 1994a, Thermogenic and secondary biogenic gases, San Juan Basin, Colorado and New Mexico—implications for coalbed gas producibility: American Association of Petroleum Geologists Bulletin, v. 78, no. 8, p. 1186–1209.

Scott, A. R., Tyler, Roger, Hamilton, D. S., Zhou, Naijiang, 1994b, Coal and coal gas resources of the Greater Green River Basin: application of an improved approach to resource estimation, *in* Sonneburg, S. A., compiler, Rocky Mountain Association of Geologists and Colorado Oil and Gas Association, First Biennial Conference, Natural Gas in the Western United States, Lakewood, Colorado, Oct 17–18, 1994, unpaginated (4 pages).

Scott, A. R., Tyler Roger, Hamilton, D. S., and Zhou, Naijiang, 1994c, Coal and in-place gas resources of the Greater Green River Basin, Wyoming and Colorado (abs.), *in* American Association of Petroleum Geologists, Annual Convention official program, v. 3, p. 253–254.

Seni, S. J., and Jackson, M. P. A., 1983, Evolution of salt structures, East Texas diapir province, Part 1: sedimentary record of halokinesis: American Association of Petroleum Geologists Bulletin, v. 67, no. 8, p. 1219–1244.

Seni, S. J., and Kreitler, C. W., 1981, Evolution of the East Texas Basin, *in* Kreitler, C. W., and others, Geology and geohydrology of the East Texas Basin, a report on the progress of nuclear waste isolation feasibility studies (1980): The University of Texas at Austin, Bureau of Economic Geology Geological Circular 81-7, p. 12–20.

Stenzel, H. B., 1951, Buried hill at Wilcox-Carrizo contact in East Texas: American Association of Petroleum Geologists Bulletin, v. 35, no. 8, p. 1815–1828.

Stenzel, H. B., 1953, The geology of Henrys Chapel Quadrangle, northeastern Cherokee County, Texas: University of Texas, Austin, Bureau of Economic Geology Publication 5305, 119 p.

Tewalt, S. J., 1986, Chemical characterization of Texas lignite: The University of Texas at Austin, Bureau of Economic Geology Geological Circular 86-1, 54 p.

Todd, T. W., and Folk, R. L., 1957, Basal Claiborne of Texas, record of Appalachian tectonism during Eocene: American Association of Petroleum Geologists Bulletin, v. 41, no. 11, p. 2545–2566.

Turcan, A. N., 1960, Estimating water quality from electrical logs: U.S. Geological Survey Professional Paper 450-C, p. 135–136.

Tyler, Roger, Ambrose, W. A., Scott, A. R., and Kaiser, W. R., 1991, Coalbed methane potential of the Greater Green River, Piceance, Powder River and Raton Basins: The University of Texas at Austin, Bureau of Economic Geology, topical report prepared for the Gas Research Institute under contract no. 5087-214-1544 (GRI-91/0315), 244 p.

Tyler, Roger, and Hamilton, D. S., 1994, Tectonic and stratigraphic setting and coal occurrence of the Upper Cretaceous Mesaverde Group and Lower Tertiary Fort Union Formation, Greater Green River Basin, *in* Tyler, Roger, Kaiser, W. R., Scott, A. R., Hamilton, D. S., McMurry, R. G., and Zhou, Naijiang, 1994, Geologic and hydrologic assessment of natural gas from coal seams in the Mesaverde Group and Fort Union Formation, Greater Green River Basin, Colorado and Wyoming: The University of Texas at Austin, Bureau of Economic Geology, topical report prepared for the Gas Research Institute (GRI-93/0320) under contract number 5091-214-2261, p. 12–79.

Tyler, Roger, Kaiser, W. R., McMurry, R. G., Nance, H. S., Scott, A. R., and Zhou, Naijiang, and Tremain, C. M., 1995a, Geologic characterization and coalbed methane occurrence: Williams Fork Formation, Piceance Basin, Northwestern Colorado: The University of Texas at Austin, Bureau of Economic Geology, annual report prepared for the Gas Research Institute under contract no. 5091-214-2261 (GRI-94/0456), 218 p.

Tyler, Roger, Kaiser, W. R., McMurry, R. G., Nance, H. S., Tremain, C. M., Scott, A. R., and Zhou, Naijiang, 1994a, Coalbed methane producibility model in the Piceance Basin: The University of Texas at Austin, Bureau of Economic Geology, draft annual report prepared for the Gas Research Institute under contract no. 5091-214-2261, 211 p.

Tyler, Roger, Kaiser W. R., Scott A. R., Hamilton D.S., and Ambrose W.A., 1995b, Geologic and hydrologic assessment of natural gas from coal: Greater Green River, Piceance, Powder River, and Raton Basins, Western United States: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 228, 219 p.

Tyler, Roger, Kaiser, W. R., Scott, A. R., Hamilton, D. S., McMurry, R. G., and Zhou, Naijiang, 1994b, Geologic and hydrologic assessment of natural gas from coal seams in the Mesaverde Group and Fort Union Formation, Greater Green River Basin, Wyoming and Colorado: The University of Texas at Austin, Bureau of Economic Geology, topical report prepared for the Gas Research Institute under contract no. 5091-214-2261 (GRI-93/0320), 120 p.

Tyler, Roger, and McMurry, R. G., 1995, Genetic stratigraphy, coal occurrence, and regional cross section of the Williams Fork Formation, Mesaverde Group, Piceance Basin, northwestern Colorado: Colorado Geological Survey, Department of Natural Resources, Open File Report 95-2, 42 p. and 1 plate.

Tyler, Roger, Scott, A. R., Kaiser, W. R., and Hamilton, D. S., 1995c, Geologic and hydrologic controls critical to coalbed methane producibility and resource assessment: comparative studies of the San Juan, Greater Green River, and Piceance Basin: Coalbed methane short course November 2–3, Austin, Texas, 402 p.

Tyler, Roger, Scott, A. R., Kaiser, W. R., and McMurry, R. G., 1997, The application of a coalbed methane producibility model in defining coalbed methane exploration fairways and sweet spots: examples from the San Juan, Sand Wash, and Piceance Basins: The University of Texas at Austin, Bureau of Economic Geology, Report of Investigations No. 244, 59 p.

Tyler, Roger, Scott, A. R., Kaiser, W. R., Nance, H. S., McMurry, R. G., Tremain, C. M., and Mavor, M. J., 1996, Geologic and hydrologic controls critical to coalbed methane producibility and resource assessment: Williams Fork Formation, Piceance Basin, Northwest Colorado: The University of Texas at Austin, Bureau of Economic Geology topical report prepared for the Gas Research Institute under contract no. 5091-214-2261, 398 p.

Tyler, Roger, Zhou, N. J., McMurry, R. G., Hawkins, G. J., Jackson, M. L. W., and Tremain, C. M., 1992, Selected references related to coalbed methane in the Greater Green River, Piceance, Powder River, Raton, and San Juan Basins: Colorado Geological Survey, Department of Natural Resources Information Series No. 35, 77 p.

Vormelker, R. S., 1979, Mid-Wilcox channel: deep exploration potential: South Texas Geological Society Bulletin, v. 20, no. 2, p. 10–40.

Winker, C. D., 1982, Cenozoic shelf margins, northwestern Gulf of Mexico: Gulf Coast Association of Geological Societies Transactions, v. 32, p. 427–448.

CONVERSION CHART

Nonmetric unit		Conversion factor		Metric unit
feet (ft)	×	0.3048	=	meters (m)
inches (inch)	×	2.540	=	centimeters (cm)
miles (mi)	×	1.609	=	kilometers (km)
feet/mile (ft/mi)	×	0.1894	=	meters/kilometer (m/km)
square miles (mi^2)	×	2.589	=	square kilometers (km^2)
cubic feet (cf)	×	0.02832	=	cubic meters (m^3)
short tons	×	0.9072	=	metric tons (t)
pounds per square inch (psi)	×	6.895	=	kilopascals (kPa)
psi/ft	×	22.62	=	kilopascals per meter (kPa/m)

APPENDIX A. RECOMMENDED EXPLORATION, DRILLING, AND DEVELOPMENT PROGRAM FOR EAST-CENTRAL TEXAS COAL BASINS

Geologic and Hydrologic Basin Analysis and Reservoir Characterization

As a result of this evaluation, we recommend that in collaboration with a Texas operator we incorporate detailed basin analysis by describing the geologic and hydrologic controls on coalbed methane producibility in the selected areas and then apply the producibility model in defining exploration fairways. The drilling program will provide us with test data including geophysical logs, seismic surveys, coal rank, coal gas composition, isotopic, gas content, and water analyses, drill-stem tests and/or pressure data, and other data that may be available for complete coalbed methane basin analysis. These data will be incorporated into the regional basin analysis framework and interpreted in the context of the coalbed methane producibility model to accurately define the coalbed methane potential of the area. The integration of regional coal-occurrence, structure, fracture-attribute, potentiometric-surface, pressure-gradient, hydrochemical, coal-rank, gas-composition, and production maps will help identify additional exploration fairways throughout Texas. If the coalbed methane exploration and development program does not take into account the variability of all these controlling parameters, then the risk exists that the exploration could (1) condemn a resource that exists but was not correctly assessed because of a poorly chosen test basin and site, or (2) achieve some success, but not the full potential, because an interpreted model for the small area did not fit the larger basin-scale setting.

Depositional models will facilitate prediction of coal deposits where data are sparse. Some operators have related coal permeability to depositional setting; thus, better knowledge of depositional setting may allow more informed estimates of permeability. Data on coal-bed continuity would help to select continuous coal beds for completion and consequent higher potential cumulative production. Aside from the importance of sandstone distribution to coal occurrence, sandstone distribution relative to fracture orientation and density, pressure regime, particularly pressure transitions, coal rank, and gas-dryness index would be of benefit to operators targeting tight gas sandstones.

An understanding of regional ground-water circulation patterns should lead to more efficient exploration and development. From them, no-flow boundaries (permeability contrasts) can be inferred for consequent delineation of additional fairways favorable for hydrocarbon accumulation and trapping. Furthermore, the extent of meteoric circulation can be used to assess the relative importance of basin-centered gas. Chemical composition of produced waters will be used to assess possible environmental impact of their disposal and to help design disposal wells to minimize scaling and plugging of host-rock permeability.

Finally, coal-rank data combined with net-coal thickness will allow estimates of the amount of thermogenic gas generated and thus available for resorption and conventional trapping in various parts of the basin. The compositional variability and isotopic composition of coal gases can be used to determine coal gas origins and possible migration directions. The distribution of wet gas components, liquid hydrocarbons, and waxes is a function of permeability and hydrodynamics as well as rank and maceral content. Out of a better understanding of the nature and extent of bacterial activity in coal beds may come strategies for bacterial removal of wax from production strings and microbial enhancement of coalbed methane recovery Scott (1995).

We think that a detailed basin analysis incorporating the coalbed methane producibility model can confirm or negate fairways and sweet spots in Texas basins that potentially have higher coalbed methane productivity. Test drilling will confirm productivity. In summary, our basin analysis investigations of the geology, hydrology, and geochemistry of the east-central Texas basins will serve to select fairways in these basins for further exploration and development. Above all, the focus remains on delineating interrelated geologic and hydrologic controls that determine the economic feasibility of coalbed methane production. Successful application of advanced completion technologies and optimal site selection within a basin are highly dependent on these controls.

Drilling and Testing of Coabed Methane Producibility Fairway

Through targeting and drilling site-specific sweet spots in east-central Texas coal basin, in collaboration with Texas operators, the coalbed methane potential may be realized. Data accumulated and generated from the test sites will confirm or negate areas and zones of extraordinary or limited coalbed methane potential. Extraordinary coalbed methane production will require dynamic ground-water flow through coals of high thermal maturity (rank) and high gas content orthogonally toward flow barriers accompanied by generation of secondary biogenic gas and conventional trapping of migrated and solution gases along those barriers. The resulting interplay will lead to high gas contents or even fully gas-saturated coals for consequent high productivity. When flow barriers (regional hingelines, fault systems, facies changes and/or discharge areas) are orthogonal to flow, the gas-gathering area is large and efficiently swept of gas for trapping along them. In east-central Texas, conventional trapping in areas of upward vertical flow potential will play a much more important role in coalbed methane production than may have been previously recognized. There is subsequent to basin uplift and cooling a need for additional sources of gas beyond that initially sorbed on the coal surface to achieve high production. Those additional sources of gas are migrated conventionally trapped, secondary biogenic, and solution gases. In other words, the parts of the basins with the best potential for drilling and development should be those basinward of where outcrop and subsurface coals are in good hydraulic communication for consequent generation of secondary biogenic gas, advective gathering and transport of gas, and subsequent basinward resorption and conventional trapping, which promote fully gas-saturated coals and high production. Importantly, the Wilcox Eocene sandstones are known as important hydrocarbon producers along the Gulf Coast. Migrated thermogenic gases may play a more significant role in coalbed methane resource development than previously expected.

However, coalbed methane producibility maybe limited, for example, in areas or zones of low permeability associated with hydrocarbon overpressure and mineral-filled or annealed cleats. A drilling, exploration, and development program will illuminate such areas of limited coalbed methane potential. Moreover, permeability will also be reduced where maximum horizontal compressive stresses are perpendicular to face cleat orientations. Coalbed methane producibility may also be inhibited in areas of exceptionally high permeability associated with meteoric recharge. Therefore, coalbed methane wells located near the outcrop belt, near water-saturated sandstones, or along major fault systems favorably oriented to accept recharge may have excessive water production. The presence of a dynamic ground-water flow system, either present-day or paleohydrologic regimes, is critical to exceptionally high coalbed methane production when migration and conventional trapping of thermogenic gases have occurred in these basins. In these scenarios, where there is limited potential for coalbed methane production, it might be feasible to comingle methane produced from coal seams with gas from conventional gas sands. Co-production of coalbed methane along with conventional natural gas from the same borehole could offer a more cost-effective approach to recovering both sources of gas. Importantly, the drilling and testing program and application of the producibility model will provide the operators with a rationale for future exploration drilling and development strategies.