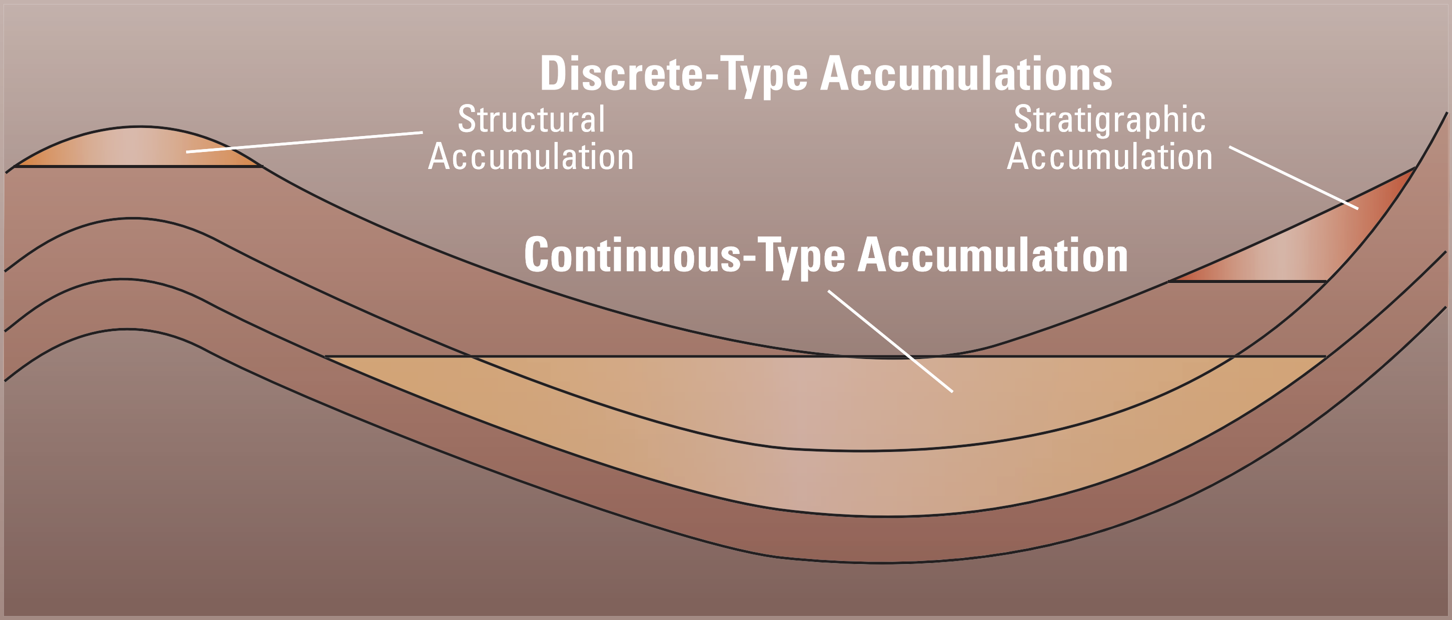
# Is There a Basin-Centered Gas Accumulation in Cotton Valley Group Sandstones, Gulf Coast Basin, U.S.A?

## Geologic Studies of Basin-Centered Gas Systems

U.S. Geological Survey Bulletin 2184-D




U.S. Department of the Interior
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*By* Charles E. Bartberger, Thaddeus S. Dyman, *and* Steven M. Condon

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*Edited by* Vito F. Nuccio *and* Thaddeus S. Dyman

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# Is There a Basin-Centered Gas Accumulation in Cotton Valley Group Sandstones, Gulf Coast Basin, U.S.A.?

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## Abstract

The U.S. Geological Survey (USGS), in cooperation with the U.S. Department of Energy, is reevaluating the resource potential of selected domestic basin-centered gas accumulations. Basin-centered gas accumulations are characterized by presence of gas in extensive low-permeability (tight) reservoirs in which conventional seals and trapping mechanisms are absent, abnormally high or low reservoir pressures exist, and gas-water contacts are absent.

In 1995, the USGS assessed one basin-centered gas play and two conventional plays within the trend of Jurassic and Cretaceous Cotton Valley Group fluvial-deltaic and barrier-island/strandplain sandstones across the onshore northern Gulf of Mexico Basin. Detailed evaluation of geologic and production data provides new insights into these Cotton Valley plays.

Two Cotton Valley sandstone trends are identified based on reservoir properties and gas-production characteristics. Transgressive blanket sandstones across northern Louisiana have relatively high porosity and permeability and do not require fracture stimulation to produce gas at commercial rates. South of this trend, and extending westward into eastern Texas, massive sandstones of the Cotton Valley trend exhibit low porosity and permeability and require fracture stimulation. The high permeability of Cotton Valley blanket sandstones is not conducive to the presence of basin-centered gas, but low-permeability massive sandstones provide the type of reservoir in which basin-centered gas accumulations commonly occur.

Data on source rocks, including burial and thermal history, are consistent with the interpretation of potential basin-centered gas within Cotton Valley sandstones. However, pressure gradients throughout most of the blanket- and massive-sandstone trends are normal or nearly normal, which is not characteristic of basin-centered gas accumulations.

The presence of gas-water contacts in at least seven fields across the blanket-sandstone trend together with relatively high permeabilities and high gas-production rates without fracture stimulation indicate that fields in this trend are conventional. Within the tight massive-sandstone trend, permeability is sufficiently low that gas-water transition zones are vertically extensive and gas-water contacts either have not been encountered or are poorly defined. With increasing depth through these transition zones, gas saturation decreases and water saturation increases until eventually gas saturations become sufficiently low that, in terms of ultimate cumulative production, wells are noncommercial. Such progressive increase in water saturation with depth suggests that poorly defined gas-water contacts probably are present below the depth at which wells become noncommercial. The interpreted presence of gas-water contacts within the tight, Cotton Valley massive-sandstone trend suggests that gas accumulations in this trend, too, are conventional, and that a basin-centered gas accumulation does not exist within Cotton Valley sandstones in the northern Gulf Basin.

## Introduction

The U.S. Geological Survey is reevaluating the potential for occurrence of continuous-type basin-centered gas accumulations in selected basins in the United States since completion of the USGS 1995 National Petroleum Assessment. This effort, which is partly funded by the U.S. Department of Energy, might result in identification of new continuous-type gas plays and petroleum systems or reevaluation of existing plays.

As part of the 1995 National Assessment of United States Oil and Gas Resources by the USGS, Schenk and Viger (1996) identified one continuous-type basin-centered gas play and two conventional gas plays (fig. 1) within the Cotton Valley Group sandstone trend in eastern Texas and northern Louisiana. The purpose of this report is to reevaluate the 1995 USGS play definitions and parameters for establishing those plays through more extensive evaluation of data on reservoir properties, reservoir pressures, gas and water recoveries, gas-production rates, and gas-water contacts in Cotton Valley sandstones. Data favorable and unfavorable for the presence of continuous-type basin-centered gas accumulations are summarized. No attempt is

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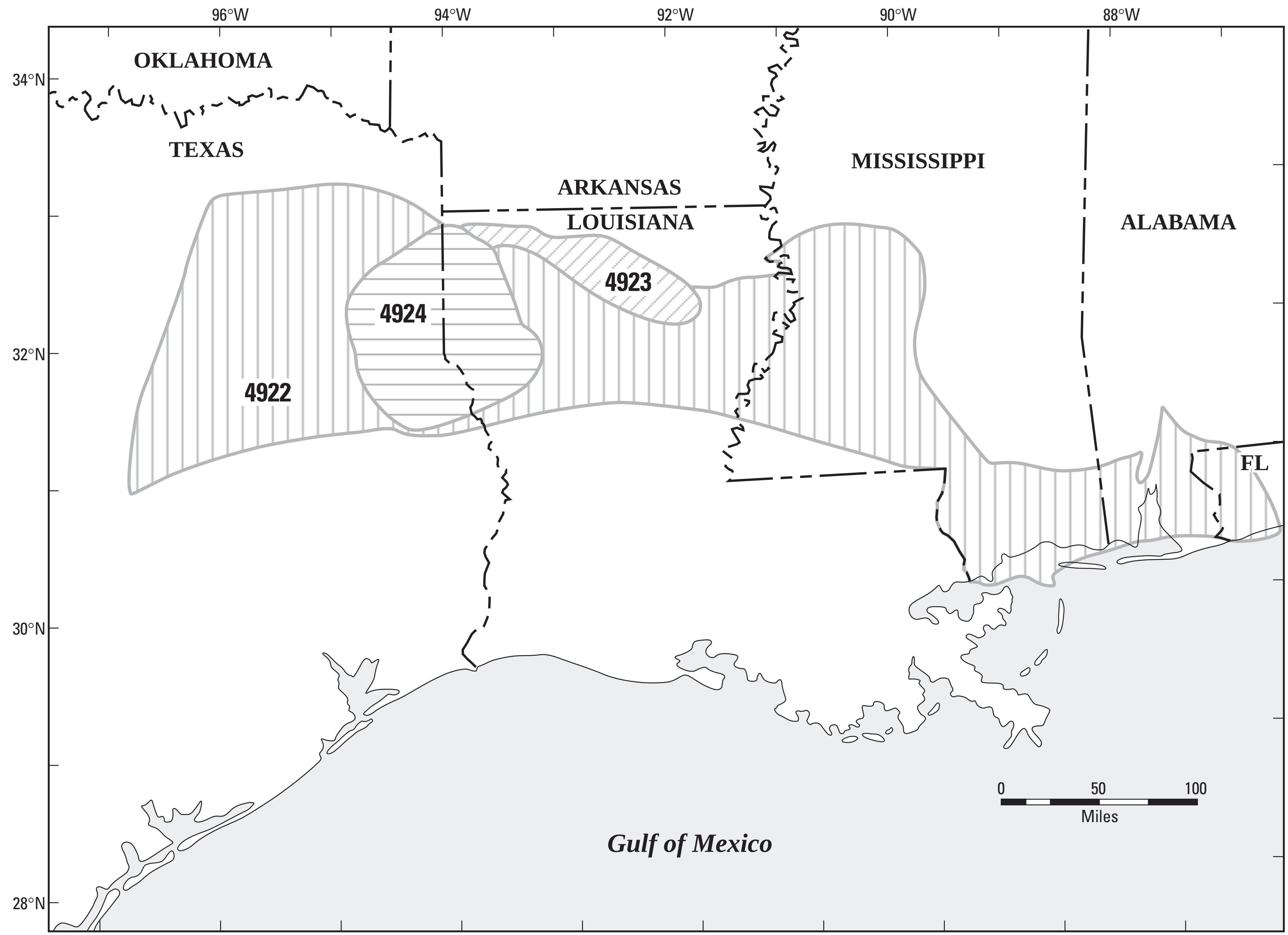



**Figure 1.** Map of north-central Gulf Coast Basin from Schenk and Viger (1996) showing outlines of three Cotton Valley Group plays identified by U.S. Geological Survey in the 1995 National Assessment of United States oil and gas resources. Shown are the Cotton Valley Blanket Sandstones gas play (4923) identified as a continuous gas play, and the Cotton Valley Salt Basins gas play (4922) and Cotton Valley Sabine Uplift gas play (4924) identified as conventional gas plays.

made, however, to identify new plays and petroleum systems or to assess gas resources for potential plays.

From a regional perspective, two productive trends of Cotton Valley sandstones are recognized based on sandstone-reservoir properties, gas-production rates, and necessity of hydraulic-fracturing treatments to achieve commercial production. Across northernmost Louisiana, so-called Cotton Valley blanket sandstones have sufficiently high porosity and permeability that commercial rates of gas production can be obtained without artificial well stimulation. South of this area, in northern Louisiana, and extending westward across the Sabine uplift into northeastern Texas, sandstones in the Cotton Valley massive-sandstone trend have poorer reservoir properties and require hydraulic-fracture treatments to achieve commercial rates of gas production. Because basin-centered, continuous gas accumulations characteristically occur within low-permeability reservoirs, the tight, Cotton Valley massive-sandstone trend across northern Louisiana and northeastern Texas is an ideal setting in which to look for potential basin-centered gas accumulations.

### Data Sources

Interpretations and conclusions presented in this report are based on data from published literature and limited conversations with industry personnel, together with geologic and engineering data accessible in a publicly available CD-ROM database from IHS Energy Group (PI/Dwights Plus, a trademark of Petroleum Information/Dwights, d.b.a. IHS Energy Group). PI/Dwights Plus data evaluated for this report are current through February 2000. Primary data from PI/Dwights Plus pertinent to this study are results of drill-stem and production tests in Cotton Valley sandstones reported for individual wells. Because well-completion records depend on information provided by operators, well data in PI/Dwights Plus might be incomplete.

## Acknowledgments

This work is funded by the U.S. Department of Energy, National Energy Technology Laboratory, Morgantown, W. Va. (contract nos. DE-AT26-98FT40031 and DE-AT26-98FT40032), and by the U.S. Geological Survey Central Energy Team. Laura Biewick of the USGS provided instruction and assistance in using ArcView software to evaluate Cotton Valley well and test data. Gregory Zerrahn and Joseph Lott, geologists with Palmer Petroleum, Shreveport, La., assisted in obtaining reports, maps, and literature. We thank Al Brake, BP Amoco, and Al Taylor, Nomad Geosciences, for providing invaluable information on characteristics of Cotton Valley tight-gas accumulations. We acknowledge helpful reviews of this manuscript by Chuck Spencer, Curt Huffman, and Katharine Varnes of the USGS.

## Continuous-Type Gas Accumulations

It is important to identify continuous-type gas accumulations because resource assessment for such gas accumulations is conducted using different methodology than that used for conventional fields. Continuous-type gas accumulations generally occur within an extensive volume of reservoir rock with spatial dimensions equal to or exceeding those of conventional hydrocarbon plays. The definition of continuous gas accumulations used here is based on geology rather than on government regulations defining low-permeability (tight) gas accumulations. Common geologic and production characteristics of continuous gas accumulations include their occurrence downdip from water-saturated rocks, lack of conventional traps or seals, reservoir rocks with low matrix permeability, presence of abnormal pressures, large in-place volumes of gas, and low recovery factors (Schmoker, 1996).

Continuous gas plays were treated as a separate category in the U.S. Geological Survey 1995 National Petroleum Assessment and were assessed using a specialized methodology (Schmoker, 1996). These continuous plays are diverse geologically and fall into several categories including coal-bed gas, biogenic gas, fractured-shale gas, and basin-centered gas accumulations. This report focuses on the potential for basin-centered gas within Cotton Valley sandstones.

### Basin-Centered Gas Accumulations

From studies of hydrocarbon-productive basins in the Rocky Mountain region, Law and Dickinson (1985) and Spencer (1987) identified characteristics of basin-centered gas accumulations that distinguish them from conventional ones. Basin-centered gas accumulations:

1. Are geographically large, spanning tens to hundreds of square miles in aerial extent, typically occupying the central, deeper parts of sedimentary basins.
2. Occur in reservoirs with low permeability—generally less than 0.1 millidarcy (mD)—such that gas cannot migrate by buoyancy.
3. Lack downdip gas-water contacts because gas is not held in place by buoyancy of water. Consequently, water production is low or absent. If water is produced, it is not associated with a distinct gas-water contact.
4. Commonly occur in abnormally pressured reservoirs (generally overpressured, but occasionally underpressured).
5. Contain primarily thermogenic gas, and where overpressure is encountered, the overpressuring mechanism is thermal generation of gas.
6. Occur structurally downdip from water-bearing reservoirs that are normally pressured or occasionally underpressured.
7. Lack traditional seals and trapping mechanisms.
8. Have gas-prone source rocks proximal to the low-

permeability reservoirs such that migration distances are short.

9. Occur in settings such that the tops of such gas accumulations occur within a narrow range of thermal maturity, usually between a vitrinite reflectance ($R_o$) of 0.75 and 0.9 percent.

What causes a basin-centered, continuous gas accumulation to form? The most common scenario involves low-permeability reservoirs in which overpressure develops in response to thermal generation of gas. Gas-prone source rocks generally must be associated with, or proximal to, low-permeability reservoirs, and this sequence of source and reservoir rock must be buried to a depth sufficient for the source rocks to generate gas. Overpressure develops because thermal generation of gas occurs at a rate that exceeds the rate at which gas is lost updip by migration through the low-permeability reservoir. As overpressure develops, any free water in pores of the tight reservoir is forced out updip into higher permeability, normally pressured, water-bearing strata. Only bound, irreducible water remains in the tight-gas reservoir. Permeability is sufficiently low within the tight reservoir that gas does not migrate through it by buoyancy as it does through conventional reservoirs with higher permeabilities (Gies, 1984; Spencer, 1987; Law and Spencer, 1993). Instead, gas migrates slowly through the tight-gas reservoir with movement caused by the pressure differential between the region of high-pressure gas generation and the normally pressured, higher permeability, water-bearing rocks updip where gas does migrate upward rapidly by buoyancy. Thus, because of its inherent low permeability, a basin-centered gas reservoir itself retards the upward migration of gas, in effect forming its own leaky seal, and maintaining overpressured conditions.

This scenario probably describes an ideal, end-member situation. In some cases, for example, basin-centered gas accumulations have subnormal reservoir pressures resulting from significant tectonic uplift of strata in the basin. For a basin that is tectonically active and in an intermediate stage of uplift, it might be possible to find a basin-centered gas accumulation that is normally pressured. It is also possible that particular gas accumulations might have only some of the characteristics for basin-centered gas described above and that differentiating between basin-centered and conventional accumulations could be difficult and subjective. It is with this understanding that the potential for basin-centered gas in Cotton Valley sandstones is evaluated.

## Method for Evaluating Potential of Basin-Centered Gas in Cotton Valley Group Sandstones

One of the main requirements for occurrence of a basin-centered, continuous gas accumulation is the presence of a regional seal to trap gas in a large volume of rock across a wide geographic area. Within that large volume of rock, discrete gas accumulations having conventional seals and gas-water contacts are absent, and occurrence of gas often cuts across stratigraphic units. In classic basin-centered gas accumulations (Law and Dickinson, 1985; Spencer, 1987; Law and Spencer, 1993), the regional seal is provided by the low permeability of the reservoir itself. To evaluate the potential for the presence of a continuous gas accumulation within Cotton Valley Group sandstones, therefore, it is necessary to examine reservoir properties of Cotton Valley sandstones across the northern Gulf Coast Basin. Because reservoir properties of Cotton Valley sandstones are governed by diagenetic characteristics, which are controlled primarily by depositional environment, it is helpful to understand Cotton Valley depositional systems and related diagenetic patterns.

Although gas production from Cotton Valley sandstones seems to occur from discrete fields, it is necessary to determine if those fields are separate, conventional accumulations or so-called “sweet spots” within a regional, continuous gas accumulation. Thus, it is essential to understand what characterizes the apparent productive limits of existing Cotton Valley gas fields, including the presence or absence of gas-water contacts. For some fields in which gas-water contacts are not reported, an attempt was made to determine the presence or absence of gas-water contacts by examining fluid recoveries from drill-stem or production tests in wells on the flanks of those fields. The goal was to determine if certain Cotton Valley fields that produce from tight-gas sandstones are flanked by dry holes that tested water only, without gas, suggesting presence of a gas-water contact. To analyze test data spatially, data from PI/Dwights Plus were imported into ArcView 3.2, running on a desktop computer. While viewing the map display, test results from any particular well could be examined.

Finally, because continuous gas accumulations often are characterized by overpressure associated with thermal generation of gas from source rocks in proximity to low-permeability reservoirs, it is important to evaluate the presence and quality of potential source rocks, burial and thermal history of those source rocks, and reservoir-pressure data.

## Geologic Setting of Cotton Valley Group

The Cotton Valley Group is an Upper Jurassic to Lower Cretaceous sequence of sandstone, shale, and limestone that underlies much of the northern Gulf of Mexico coastal plain from eastern Texas to Alabama (figs. 2 and 3). Cotton Valley strata occur only in the subsurface and form a sedimentary wedge that thickens southward into the Gulf Basin from a zero edge in southern Arkansas and eastern Texas (fig. 2). The downdip limit of the Cotton Valley Group has not been delineated yet by drilling. The depth to top of the Cotton Valley ranges from about 4,000 ft below sea level near the

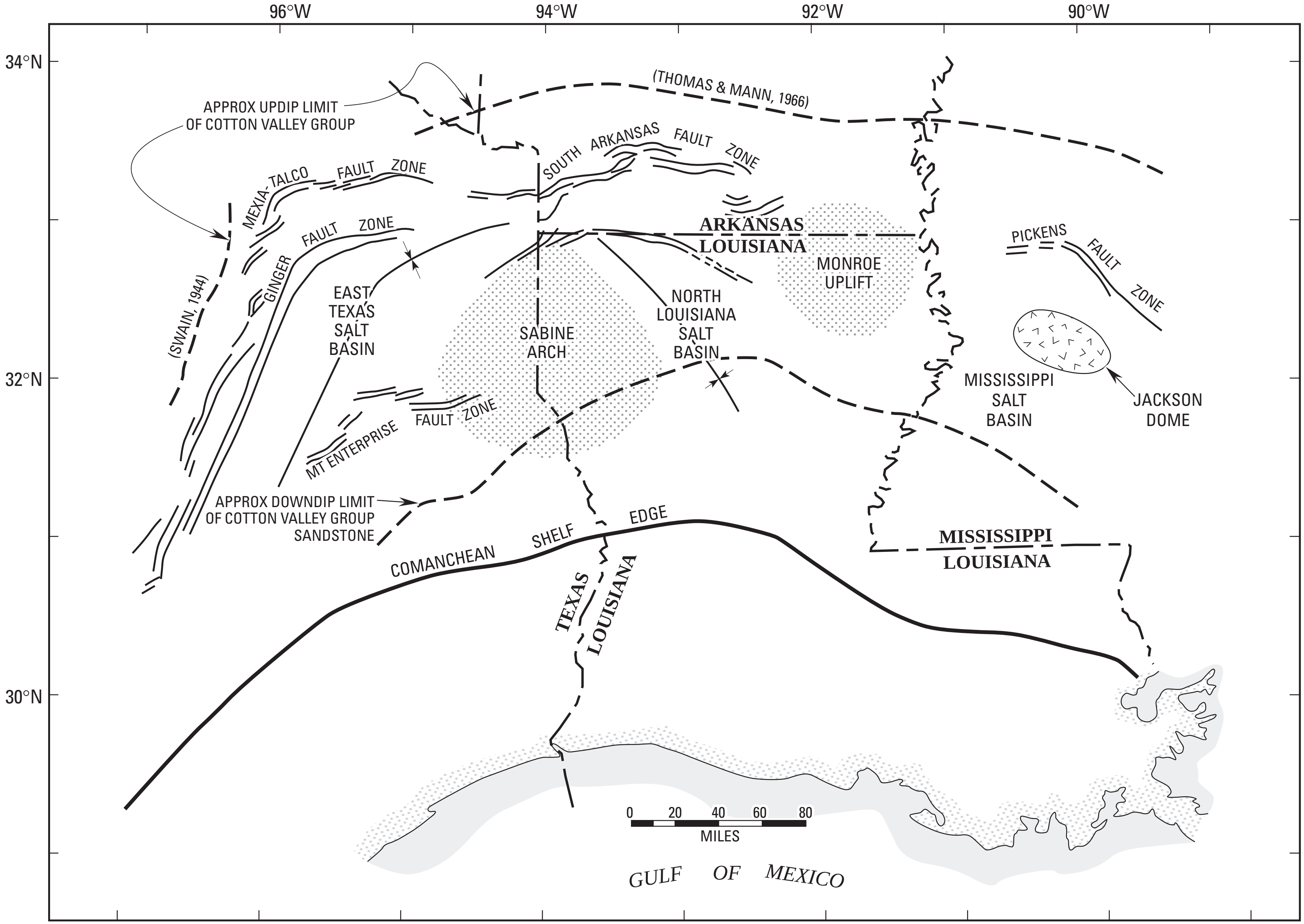



**Figure 2.** Index map of north-central Gulf Coast Basin, modified from Dutton and others (1993), showing major tectonic features. Sabine and Monroe uplifts were not positive features during deposition of Cotton Valley Group sediments. Cotton Valley depocenters were located across the entire northern Gulf Basin from eastern Texas to Alabama. Salt movement in East Texas and North Louisiana Salt Basins was contemporaneous with deposition of Cotton Valley Group clastic sediments. The Cotton Valley Group is an entirely subsurface sequence of strata with approximate updip limits shown here.

updip zero edge to more than 13,000 ft below sea level along the southern margins of the East Texas and Louisiana Salt Basins (figs. 2 and 4). In southeastern Mississippi, the top of the Cotton Valley occurs at nearly 20,000 ft below sea level. The greatest thickness of Cotton Valley rocks penetrated exceeds 5,000 ft in southeastern Mississippi (Moore, 1983).

The Cotton Valley Group and overlying Travis Peak (Hosston) Formation represent the first major influx of terrigenous clastic sediments into the Gulf of Mexico Basin following its initial formation during continental rifting in Late Triassic time (Salvador, 1987; Worrall and Snelson, 1989). Earliest sedimentary deposits in East Texas and North Louisiana subbasins (figs. 2 and 3) include upper Triassic nonmarine red beds of the Eagle Mills Formation, the thick Middle and Upper Jurassic evaporite sequence known as Werner Formation (anhydrite) and Louann Salt, and the nonmarine Norphlet Formation. Following a major regional marine transgression across the Norphlet, Upper Jurassic Smackover Formation regressive carbonates were deposited, capped by red beds and evaporites of the Buckner Formation (fig. 3). A subsequent minor marine transgression is recorded by the Gilmer Limestone or Cotton Valley Formation in eastern Texas, although equivalent facies in northern Louisiana and Mississippi are terrigenous clastics known as the Haynesville Formation. The marine Bossier Shale, lowermost formation of the Cotton Valley Group (figs. 3 and 5) was deposited conformably on Gilmer-Haynesville strata.

Louann Salt became mobile as a result of sediment loading and associated basinward tilting. Salt movement was initiated during Smackover carbonate deposition and became more extensive with influx of Cotton Valley clastics (McGowen and Harris, 1984). Many Cotton Valley and Travis Peak fields in eastern Texas, Louisiana, and Mississippi are structural or combination traps associated with Louann Salt structures. Salt structures range from small, low-relief salt pillows to large, piercement domes (McGowen and Harris, 1984; Kosters and others, 1989).

The Sabine uplift is a broad, low-relief, basement-cored arch separating the East Texas and North Louisiana Salt Basins (figs. 2 and 4). With vertical relief of 2,000 ft, the Sabine uplift has a closed area exceeding 2,500 $mi^2$ (Kosters and others, 1989). Isopach data across the uplift indicate that it was a positive feature during deposition of Louann Salt in the Jurassic but that primary uplift occurred in late, mid-Cretaceous (101 to 98 Ma) and early Tertiary time (58 to 46 Ma) (Laubach and Jackson, 1990; Jackson and Laubach, 1991). As a high area for the past 60 m.y., the Sabine uplift has been a focal area for hydrocarbon migration in the northern Gulf Basin during that time. Numerous smaller structural highs on the uplift in the form of domes, anticlines, and structural noses provide traps for hydrocarbon accumulations, including many gas fields in Cotton Valley sandstones. Origins of these smaller structures have been attributed to salt deformation and small igneous intrusions, as summarized by Kosters and others (1989). Because the Louann Salt is thin across the Sabine uplift, Kosters and others (1989) suggest that most of the smaller structures across the Sabine uplift developed in association with igneous activity.

# Cotton Valley Group Stratigraphic Nomenclature

Since the first penetration of Cotton Valley strata in northern Louisiana in 1927, complex informal stratigraphic nomenclature developed as numerous Cotton Valley oil and gas fields were discovered across the region through the 1940's. Nomenclature became complex because of local stratigraphic complexities within Cotton Valley strata in northern Louisiana and also because of regional variations in Cotton Valley depositional systems across the northern Gulf Basin. Terminology established by Swain (1944) was used until the complete revision of Cotton Valley stratigraphy by Thomas and Mann (1963) and Mann and Thomas (1964). Most subsequent reports, including the classic work of Collins (1980), have used Mann-Thomas terminology. Refinements to that terminology have been contributed by Coleman and Coleman (1981) and Eversull (1985).

Cotton Valley lithofacies and associated stratigraphic nomenclature in northern Louisiana are shown in figures 5 and 6. The basal formation of the Cotton Valley Group is the Bossier Shale, a dark, calcareous, fossiliferous, marine shale. In eastern Texas, isolated turbidite sandstones occur within the Bossier Shale (Collins, 1980). Overpressured gas currently is being produced from these sandstones in a rapidly developing new play (PI Dwights Drilling Wire, Jan. 3, 2000; Exploration Business Journal, 2nd quarter, 2000). Completely encased in marine shale, these gas-charged sandstones might represent a continuous gas accumulation.

The Bossier Shale grades upward into Cotton Valley sandstones with interbedded shales. These sandstones consist of stacked barrier-island, offshore-bar, strandplain, and fluvial-deltaic sandstones and are referred to as the Terryville massive-sandstone complex in northern Louisiana by Coleman and Coleman (1981). In eastern Texas, the stratigraphically equivalent unit is called Cotton Valley Sandstone, and it consists of braided-stream, fan-delta, and wave-dominated-delta sandstones (Wescott, 1983; Coleman, 1985; Dutton and others, 1993). Across the Cotton Valley hydrocarbon-productive trend in eastern Texas and northern Louisiana, the Terryville or Cotton Valley Sandstone averages about 1,000 to 1,400 ft in thickness (Finley, 1984; Presley and Reed, 1984). Sand deposition was interrupted in Early Cretaceous time by a regional transgressive event marked by deposition of the Knowles Limestone (figs. 5 and 6). In updip areas of eastern Texas and southern Arkansas, the Knowles Limestone pinches out, and clastic rocks of the Travis Peak, or equivalent Hosston, Formation directly overly Cotton Valley sandstones (figs. 3, 5, and 6). Saucier (1985) interprets the Knowles Limestone as the uppermost formation of the Cotton Valley Group, but Coleman

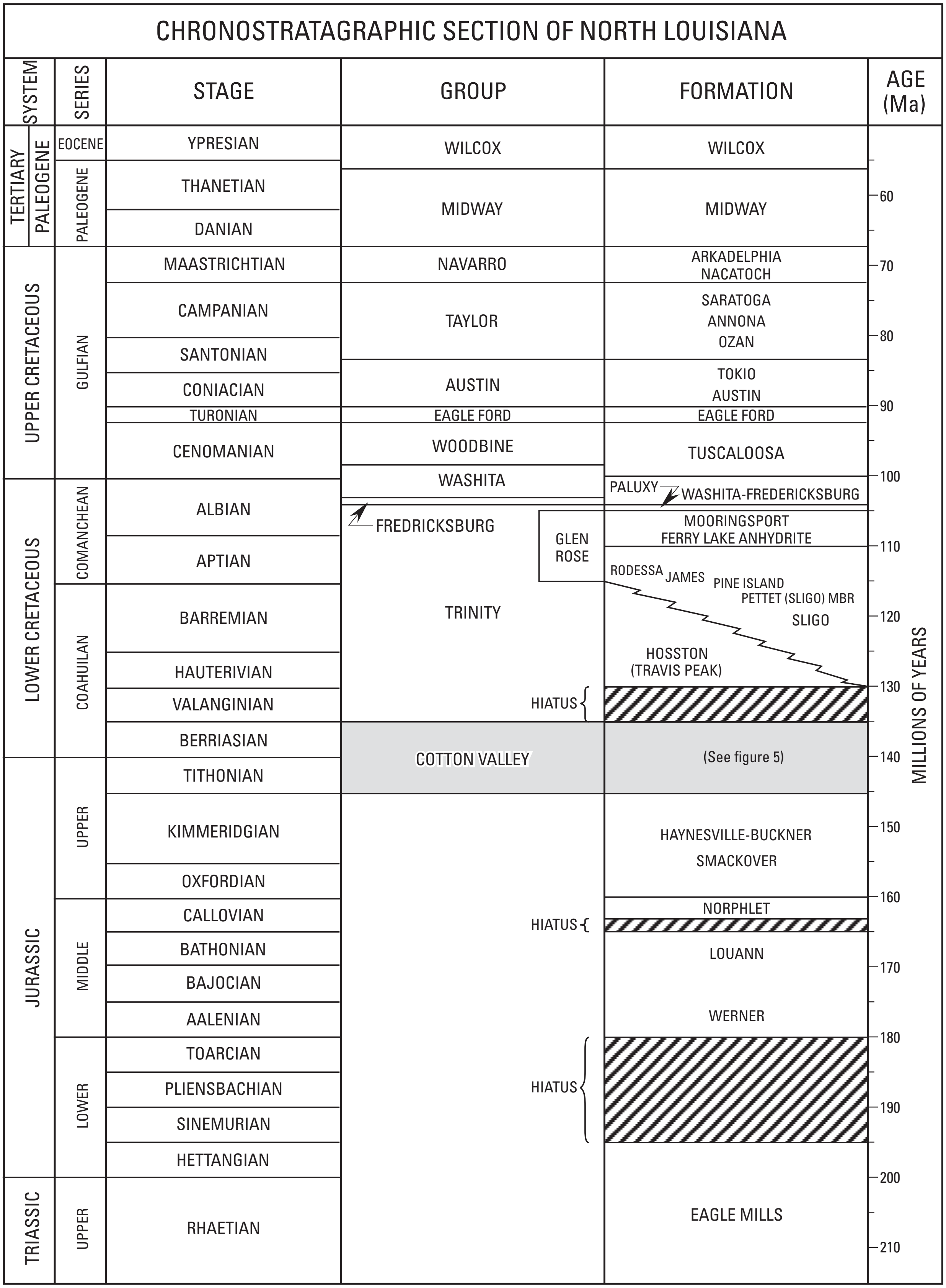



**Figure 3.** Chronostratigraphic section of northern Louisiana modified from Shreveport Geological Society (1987). Subdivisions of Cotton Valley Group shown in figure 5.

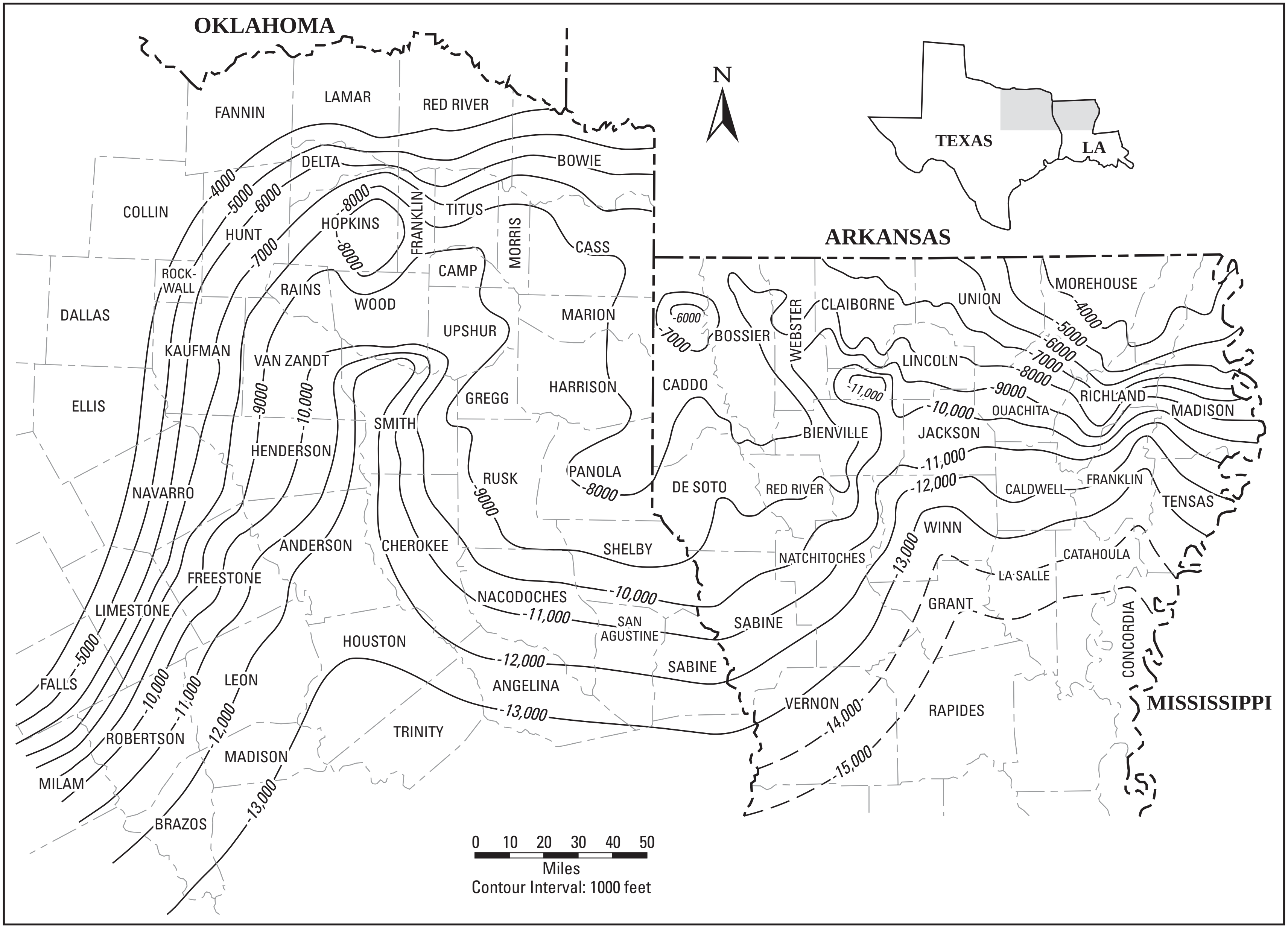



**Figure 4.** Generalized structure contours on top of Cotton Valley Group sandstone across northeastern Texas and northern Louisiana, modified from Finley (1984). Cotton Valley sandstone has been designated as "tight-gas sandstone" in all counties shown on this map with exception of 15 gas fields in northern Louisiana (fig. 8).

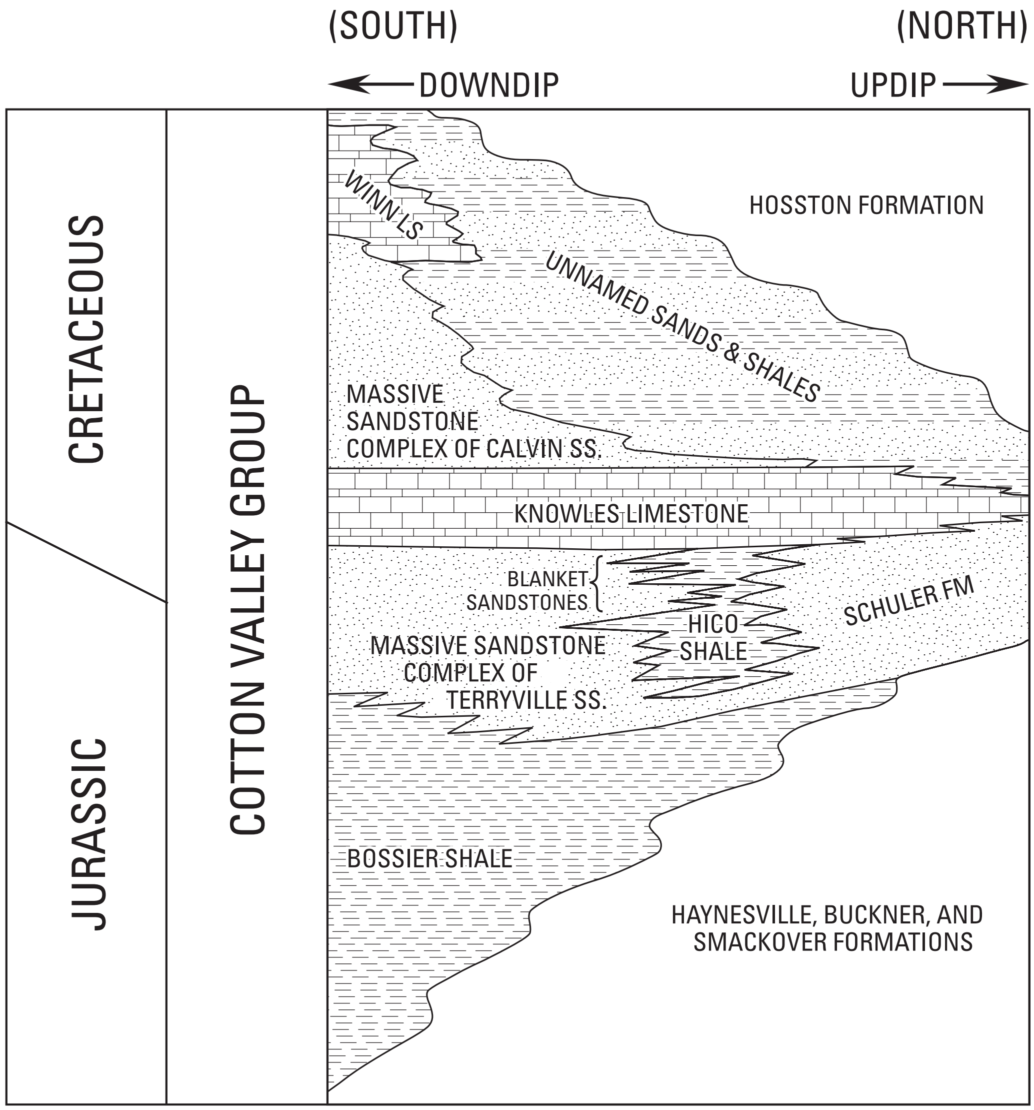



**Figure 5.** Generalized stratigraphic nomenclature of Cotton Valley Group (patterned units) in northern Louisiana, modified from Coleman and Coleman (1981). Schuler Formation and equivalents were assigned to Lower Cretaceous in mid 1980's (Herrmann and others, 1991). Prior to that time, entire Cotton Valley Group was considered to be Late Jurassic in age.

and Coleman (1981) include the stratigraphically higher Calvin Sandstone, Winn Limestone, and unnamed sands and shales within the Cotton Valley Group (figs. 5 and 6).

# Cotton Valley Group Depositional Systems

## Regional Framework

From eastern Texas to Mississippi, stacked barrier-island, strandplain, and fluvial-deltaic sandstones, known as Cotton Valley or Terryville Sandstone, reflect influx of sands from a number of depocenters. Evolution of Cotton Valley depocenters and associated paleogeography across northern Louisiana are described and illustrated by Coleman and Coleman (1981), who subdivided the Terryville Sandstone into four depositional "events" (fig. 6) based on widespread shale breaks. Across south-central Mississippi, Moore (1983) shows three sequential paleogeographic reconstructions of Cotton Valley Group sandstone deposition. Although the setting was similar, concise paleogeographic reconstructions have not been published for the East Texas Basin; however, McGowen and Harris (1984) and Wescott (1985) provide data from which basic paleogeographic maps can be constructed. Figure 7 is a regional paleo-

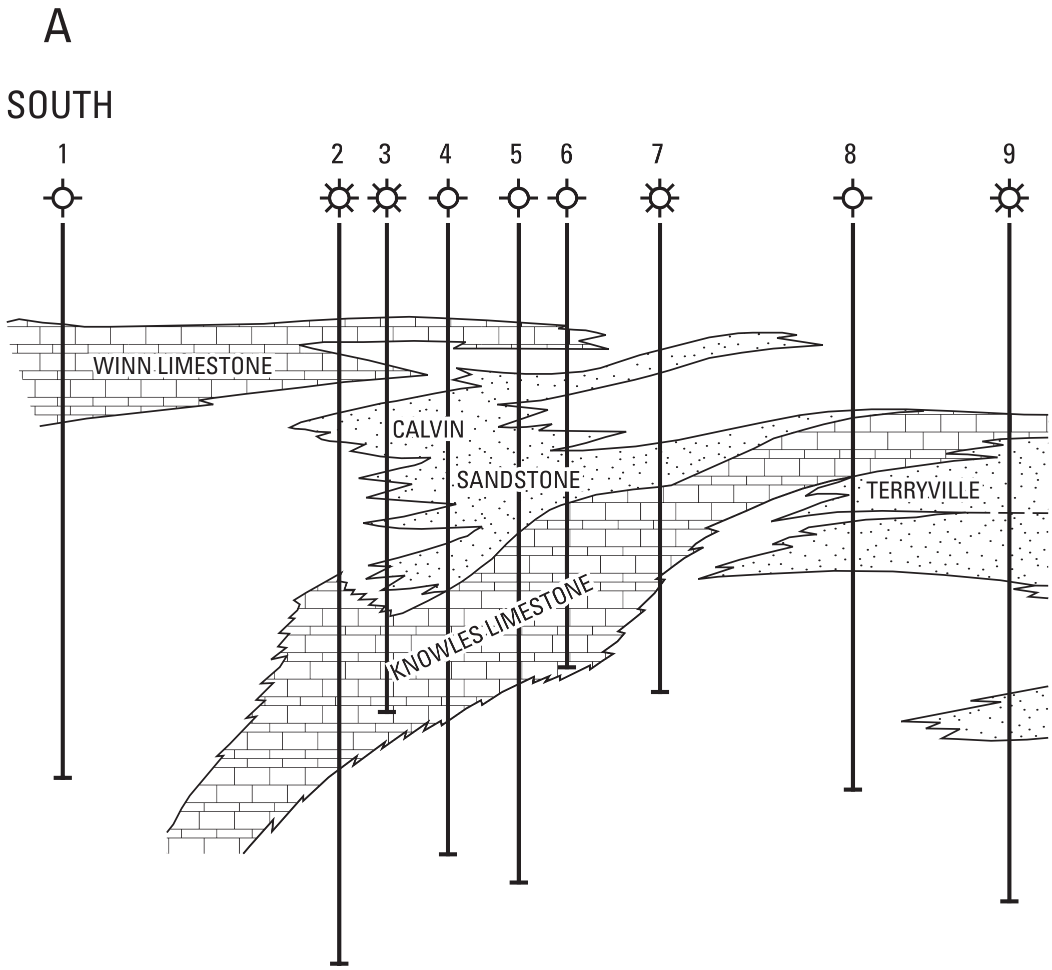
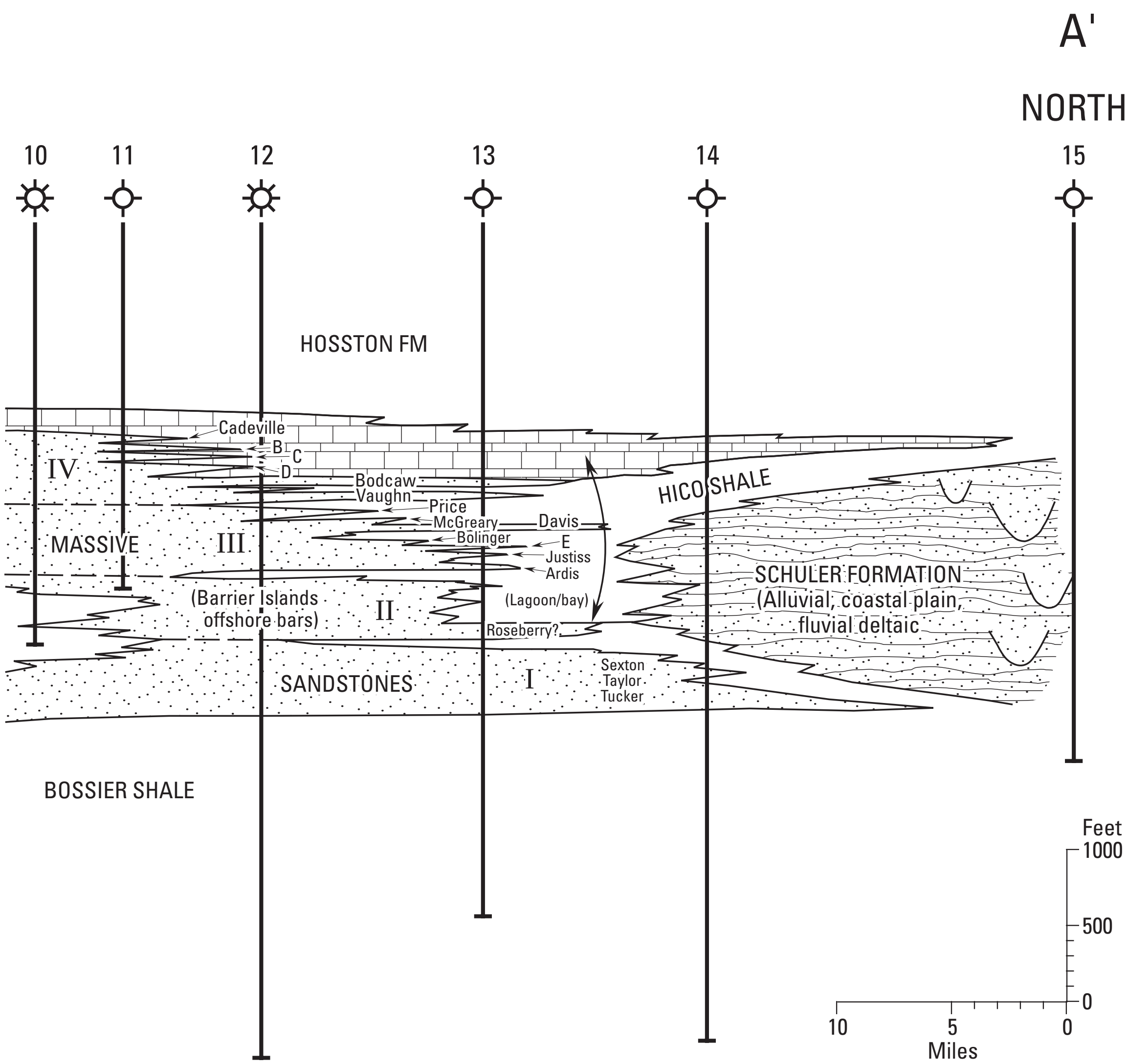



**Figure 6 (above and facing page).** North-south stratigraphic cross section of Cotton Valley Group across northern Louisiana based on data from 15 wells. Section is modified from Coleman and Coleman (1981) to show details of Cotton Valley blanket sandstones as identified and described by Eversull (1985) and Thomas and Mann (1963). Arrows indicate stratigraphic range of blanket sandstones. Line of cross section shown in figures 7 and 8.

geographic map of upper Cotton Valley depositional systems (equivalent to Terryville IV of Coleman and Coleman, 1981) across the northern Gulf Basin from eastern Texas to Mississippi based on data integrated from these various workers.

As shown in figure 7, Cotton Valley fluvial-deltaic depocenters were located in present-day northeastern Texas, south-central Mississippi, and along the Louisiana-Mississippi border. The system along the Louisiana-Mississippi border represents the ancestral Mississippi River and was a locus of major clastic influx. Large quantities of sand delivered to the marine environment by this system were transported westward by longshore currents producing an extensive east-west barrier-island or strandplain complex (Thomas and Mann, 1966). Vertical stacking of barrier-island/strandplain sands through time resulted in accumulation of the Terryville massive-sandstone complex (figs. 6 and 7). The east-west barrier-island complex across northern Louisiana sheltered a lagoon to the north from open-marine waters to the south (Thomas and Mann, 1966). The Hico Shale accumulated in the lagoon while fluvial and coastal-plain sandstones and shales of the Schuler Formation were deposited in continental environments north of the lagoon (figs. 6 and 7). Development of a similar, but smaller, lagoon associated with barrier islands—formed from longshore-transported sands in south-central Mississippi—was documented by Moore (1983) (fig. 7). In eastern Texas, during the earliest phase of Cotton Valley Sandstone deposition, small fan deltas developed along the updip margin of the East Texas Basin (McGowen and Harris, 1984; Wescott, 1985; Black and Berg, 1987). The drainage system was immature with small fan deltas formed by numerous small streams. According to McGowen and Harris (1984), fan-delta deposition persisted through Cotton Valley time along the western margin of the East Texas Basin where fan-delta deposits characterize most of the Cotton Valley Sandstone interval. Along the northern flank of the East Texas Basin, in the region of the present-day Sabine uplift, a mature drainage system




developed as fan deltas prograded basinward and evolved into a wave-dominated delta system. Sandstones of the lower part of the Cotton Valley comprising this delta system are referred to informally as the Taylor sandstone, according to Wescott (1985). After Taylor sand deposition was terminated by a subregional transgressive event, delta progradation resumed with development of a more elongate, fluvial-dominated system in the upper part of the Cotton Valley (fig. 7), referred to as the Lone Oak delta by Kast (1983).

## Blanket Sandstones of Northern Louisiana

In northern Louisiana, at least 20 distinct tongues of sandstone extend landward from barrier-island deposits of the Terryville massive-sandstone complex and become thinner northward before pinching out into shales of the Hico lagoon, as shown in figure 6. Some of these sandstones have limited geographic extent covering only part of the lagoon, whereas others extend across most or all of the lagoon and interfinger with continental deposits of the Schuler Formation on the landward side of the lagoon (Coleman and Coleman, 1981; Eversull, 1985). These sandstones have been interpreted as transgressive deposits with sand being derived from Terryville barrier islands and transported landward into the Hico lagoon during periods of relative sea-level rise and (or) diminished sediment supply (Coleman and Coleman, 1981; Eversull, 1985). These transgressive sandstones have significantly better porosity and permeability than Terryville massive sandstones from which they were derived and have been prolific producers of oil and gas from structural, stratigraphic, and combination traps discovered in the 1940's, 1950's, and 1960's across northern Louisiana (Collins, 1980; Bebout and others, 1992). Referred to informally as "blanket" sandstones (Eversull, 1985), they can be correlated readily across northern Louisiana, and, as shown in figure 6, they were given informal names by operators during drilling in the 1940's and 1950's (Sloane, 1958; Thomas and Mann, 1963; and Eversull, 1985).

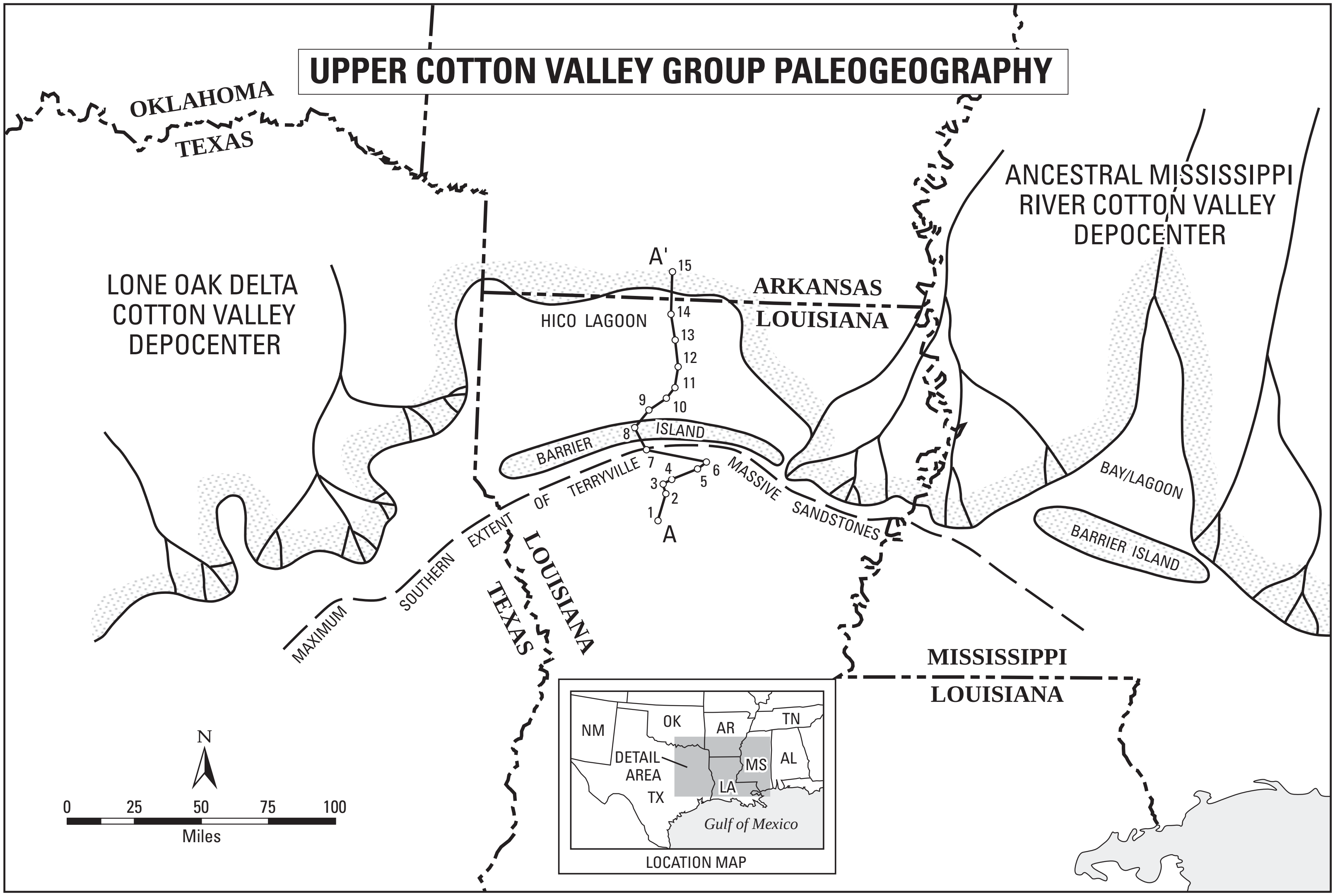



**Figure 7.** Regional paleogeographic map showing sedimentary environments of Cotton Valley Group during deposition of uppermost Cotton Valley sandstones (Terryville IV sandstone of Coleman and Coleman, 1981). Map synthesized from data of Thomas and Mann (1966), Coleman and Coleman (1981), Moore (1983), McGowen and Harris (1984), Wescott (1985), and Eversull (1985). Location of north-south stratigraphic cross section of Cotton Valley Group across northern Louisiana in figure 6 is illustrated by 15 numbered wells.

Based on isopach map trends, Eversull (1985) identified two groups of blanket sandstones. Geographically more extensive sandstones of the first group span most of the Hico lagoon and often interfinger with continental deposits of the Schuler Formation. These sandstones generally are 30 to 70 ft thick and can reach a thickness of 140 ft toward the south where they merge with barrier-island sandstones of the Terryville massive-sandstone complex. Blanket sandstones of the second group generally are less than 30 ft thick, have limited geographic extent, and most commonly occur in the eastern part of the Hico lagoon proximal to the fluvial-deltaic source. These sandstones pinch out northward into shales of the Hico lagoon. Transgressive, blanket sandstones of both groups collectively have significantly higher porosity and permeability than barrier-island sandstones of the Terryville massive-sandstone complex to the south (Collins, 1980; Bebout and others, 1992).

### Blanket- and Massive-Sandstone Productive Trends

Significant differences in reservoir properties between transgressive, blanket sandstones to the north and massive, barrier-island sandstones to the south define two different hydrocarbon-productive trends of Cotton Valley sandstones (fig. 8). Blanket sandstones have higher porosity and permeability than Terryville massive sandstones to the south. Eversull (1985) reported that blanket sandstones are cleaner and better sorted. She attributed their superior reservoir properties to high-energy reworking during transgressive events. Coleman (1985), however, reported that blanket sandstones exhibit an increase in calcite cement and clay content northward toward their pinch-out edges, and that superior reservoir properties occur because (1) clays inhibited precipitation of quartz overgrowths and (2) secondary porosity was generated through widespread dissolution of calcite cement. Absence of detrital clay coatings on sand grains in high-energy barrier-island sandstones of the Terryville massive-sandstone complex to the south, however, permitted widespread precipitation of quartz cement as syntaxial overgrowths, resulting in nearly complete occlusion of porosity (Sloane, 1958; Coleman and Coleman, 1981). Whatever the cause of porosity differences, blanket sandstones generally have sufficient porosity and permeability to flow gas or liquids on open-hole drill-stem tests (DST's) and to produce gas without fracture-stimulation treatment (Collins, 1980; Bebout and others, 1992). Terryville massive sandstones to the south and west, however, have such poor reservoir properties that they generally do not flow gas or liquids during DST's, and they require hydraulic-fracture treatments before commercial production can be achieved.

## Diagenesis of Cotton Valley Group Sandstones

Because understanding reservoir mineralogy is critical to successful wireline-log analysis and design of fracture-stimulation treatments in Cotton Valley Group sandstones, considerable attention has been devoted to understanding diagenetic patterns of Cotton Valley sandstones, especially in the low-permeability, Cotton Valley massive-sandstone trend. Focusing on those sandstones in eastern Texas, Wescott (1983) reported that Cotton Valley sandstones are very fine grained, well-sorted quartz arenites and subarkoses with monocrystalline quartz and feldspar being the primary framework components. Principal cements include quartz, calcite, clays, and iron oxides. In unraveling the complex diagenetic history of these sandstones, Wescott (1983) interpreted two major diagenetic sequences. The most common sequence is (1) formation of clay coatings—primarily chlorite—on framework grains, usually covering grains partially, not completely, (2) precipitation of syntaxial quartz overgrowths on quartz grains, (3) dissolution of unstable grains, most commonly feldspars, (4) precipitation of clays, primarily illite and chlorite with minor kaolinite, (5) precipitation of calcite cement in both relict primary pores and secondary pores, and (6) large-scale replacement of grains and cements by calcite, resulting in poikilotopic texture in which a few relict quartz grains are "floating" in calcite. In the other, less-common diagenetic sequence, which occurs primarily in cleaner, coarser grained sandstones, calcite cementation commenced early and progressed to yield a fabric with widespread replacement of grains by calcite.

Wescott (1983) classified Cotton Valley sandstones into three general groups on the basis of primary depositional texture and resulting diagenetic characteristics. In general, Wescott (1983) found that clean, well-sorted sands deposited in high-energy environments (type I) generally are nearly completely cemented by quartz and (or) calcite, have little or no porosity and permeability, and provide little reservoir potential. In some cases, these sandstones exhibit preservation of minor amounts of primary intergranular porosity from presence of authigenic chlorite coats (Hall and others, 1984). In sands deposited in lower energy environments where abundant detrital clays remained (type II), nucleation of quartz overgrowths generally was inhibited by clays. Most clay-bearing sandstones, however, contain significantly large amounts of clay, and although abundant microporosity is associated with these clays, permeability generally is low. Highest porosities, according to Wescott (1983), occur in type-III sandstones, which developed abundant secondary porosity from dissolution of unstable grains and calcite cement. Hall and others (1984), however, reported that dissolution of unstable grains often is incomplete, secondary pores generally are poorly interconnected, and these sandstones, too, have poor

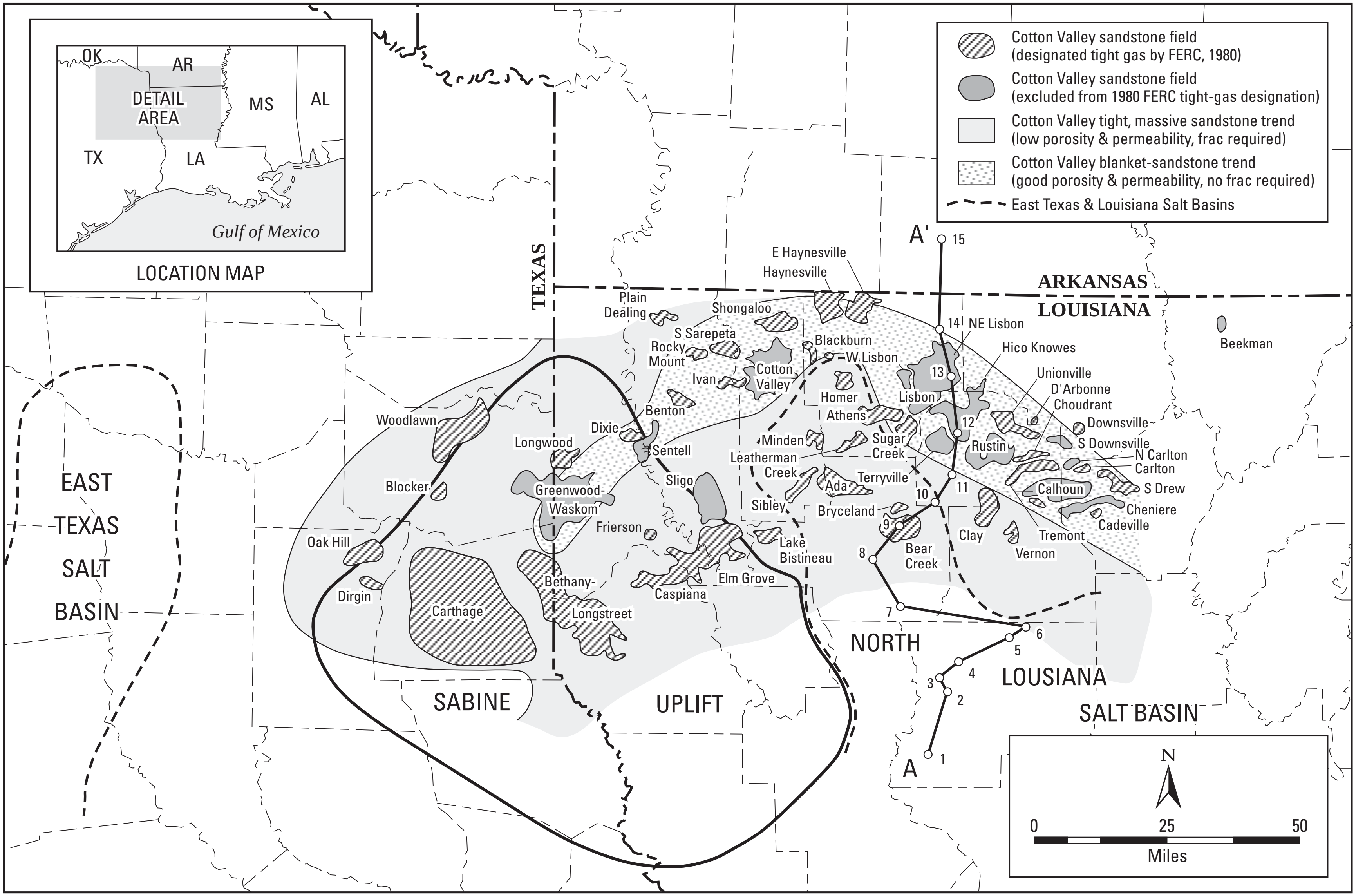



**Figure 8.** Map of northeastern Texas and northwestern Louisiana showing major fields that have produced hydrocarbons from Cotton Valley Group sandstones. Two different productive trends are recognized based on reservoir properties and resulting producing capabilities of Cotton Valley sandstone reservoirs. Fifteen fields excluded from "tight-gas" designation by FERC in 1980 are shown in solid dark-gray shading. Map modified from Collins (1980) and White and others (1992). Location of north-south stratigraphic cross section of Cotton Valley Group across northern Louisiana in figure 6 is illustrated by 15 numbered wells.

permeability and require fracture stimulation to produce gas commercially.

In northern Louisiana, as interpreted by Russell and others (1984), the upper Cotton Valley Bodcaw Tongue of the Terryville Sandstone at Longwood field on the eastern flank of the Sabine uplift experienced a virtually identical diagenetic history to that described for Cotton Valley sandstones in eastern Texas by Wescott (1983). Like Wescott (1983), Russell and others (1984) reported that nucleation of quartz overgrowths was inhibited by presence of clays, but the quantity of pore-filling clays generally is so large that permeability is low despite presence of high microporosity. Also, as in eastern Texas, the best reservoir sandstones are those that have low clay content and developed abundant secondary porosity through dissolution of unstable grains and cement. Similar diagenetic patterns in northern Louisiana also were reported for Cotton Valley sandstones at Frierson field by Sonnenberg (1976) and for the lowermost part of the Terryville Sandstone (the informal Taylor sandstone) at Terryville field by Trojan (1985). In addition to authigenic constituents reported in eastern Texas and northern Louisiana, Trojan (1985) also found small amounts of authigenic pyrite in Taylor sandstones at Terryville field. Pyrite occurs as small silt-size clusters (framboids). It is volumetrically the least abundant authigenic mineral reported by Trojan (1985), but its presence is significant because of its effect on wireline-log measurements of formation resistivity.

## Impact of Diagenetic Mineralogy on Wireline Logs

The complex diagenetic mineralogy of tight Cotton Valley sandstones prohibits use of standard calculation procedures in reservoir evaluation with wireline logs. The main difficulty is that properties of certain diagenetic constituents result in abnormally low resistivity measurements, which lead to such high calculated water saturations that productive zones appear to be wet. Major factors contributing to abnormally low resistivities in tight Cotton Valley sandstones include bound water associated with pore-filling clays or clay coatings and conductive authigenic minerals such as pyrite and ankerite (Janks and others 1985; Turner, 1997).

Pore-lining and pore-filling clays have exceptionally high ratios of surface area to volume. Large surface area and high cation-exchange capacity of clays result in formation of a double ionic layer on clay surfaces (Almon, 1979; Snedden, 1984). This bound double layer can be significantly more conductive than pore waters, resulting in abnormally low measured resistivities, especially with induction logs (Almon, 1979; Wescott, 1983). Highly conductive authigenic minerals, such as ankerite and pyrite, in Cotton Valley sandstones also cause abnormally low resistivities. Trojan (1985) found that pyrite concentrations as low as 1 percent in Cotton Valley sandstones had a dramatic effect on resistivity measurements and hence on calculated water saturations. Standard calculation methods showed that pyrite-bearing sandstones at Terryville field in northern Louisiana had water saturations in excess of 100 percent. Trojan (1985) showed that if these sandstones were pyrite-free, calculated water saturations would be closer to 50 percent. Although water saturations in productive Cotton Valley sandstones commonly are 25 to 30 percent, water-free gas production has been achieved from zones with calculated water saturations as high as 60 percent (Nangle and others, 1982; Wilson and Hensel, 1984; Dutton and others, 1993).

Porosity measurements from wireline logs also can be affected adversely from diagenetic mineral constituents in Cotton Valley sandstones. In a study of Taylor sandstones (fig. 6) at Terryville field in northern Louisiana, Ganer (1985) demonstrated the negative impact of authigenic carbonates on porosity measurements from wireline logs. Located within the porous, permeable blanket sandstone trend, Terryville field was discovered in 1954 with production from the Cotton Valley “D” sandstone (fig. 6), one of the blanket sandstones. The Taylor sandstone occurs in the lower part of the Cotton Valley Sandstone interval, and its productive potential at Terryville field was not discovered until 1978. Unlike the stratigraphically higher blanket sandstones, the Taylor sandstone has relatively poor reservoir properties similar to those of tight Cotton Valley massive sandstones to the south. Like Wescott (1983), Ganer (1985) found that, although the Taylor sandstone is predominantly a quartz sandstone, it contains authigenic carbonate cement and locally can be composed of more than 50 percent carbonate resulting in a poikilotopic texture. With abundant secondary porosity from carbonate dissolution, these carbonate-rich sandstones are the best gas producers within the Taylor sandstone interval at Terryville field. Ganer (1985) identified several different carbonate minerals in Taylor sandstones, including calcite, ankerite, and siderite. Grain densities of these minerals are 2.71, 3.00, and 3.96 g/cm$^3$, respectively. If porosity logs based on a sandstone matrix (grain density of 2.65 g/cm$^3$) are run across an interval, such as the Taylor sandstone, containing abundant carbonate constituents with higher densities, measured porosity values will be pessimistic. Working with 420 ft of conventional core from four wells at Terryville field, Ganer (1985) reported sandstone intervals with abundant carbonate constituents where log-measured porosities were close to zero, but core-measured porosities exceeded 6 percent. With complex effects of diagenetic minerals on both porosity and resistivity measurements from wireline logs, Ganer (1985) showed that a single porosity/water saturation limit is not suitable for evaluating productive potential of Cotton Valley sandstones at Terryville field. Ganer’s conclusions probably are applicable to most, or all, of the tight, Cotton Valley massive-sandstone trend across northeastern Texas and northern Louisiana.

In comparing core-derived reservoir properties with wireline-log measurements for Cotton Valley sandstones from Carthage field in eastern Texas, Wilson and Hensel (1984) reported that no apparent relationship exists between porosity and permeability. From core analyses, they noted that it is not uncommon to find a sandstone interval with 10 percent porosity and 1 to 3 mD permeability adjacent to a zone with similar porosity but with permeability less than 0.05 mD. Similarly, Ganer (1985) reported that Taylor sandstones with 8 percent porosity at Terryville field in northern Louisiana have permeabilities ranging from 0.01 to 13 mD. For Carthage field, Wilson and Hensel (1984) also noted that empirically derived values of cementation factor ($m$) and saturation exponent ($n$), used in calculation of water saturation, vary significantly from zone to zone. Wilson and Hensel (1984) derived general empirical values of $m$ and $n$ for Carthage field area to achieve more accurate log-derived estimates of water saturation. Because of such difficulties in determining water saturations from wireline logs, Presley and Reed (1984) stress that gas-pay cutoff values should be based on experience by operators in a given area.

A consequence of difficulties in accurate reservoir evaluation from conventional log analysis, of course, is that intervals capable of producing gas might be bypassed because of high calculated water saturations. For this study, the significance of these difficulties with wireline logs in tight Cotton Valley sandstones is that logs are of limited value in differentiating between gas-productive and wet intervals and therefore in identifying gas-water contacts on the flanks of Cotton Valley fields.

## Source Rocks

Little information has been published on source rocks for hydrocarbons produced from Cotton Valley reservoirs in northern Louisiana and eastern Texas. In studying the overlying Travis Peak Formation in eastern Texas, Dutton (1987) showed that shales interbedded with Travis Peak sandstone reservoirs were deposited in fluvial-deltaic settings where organic matter commonly is oxidized and not preserved. With measured values of total organic carbon (TOC) in Travis Peak shales generally less than 0.5 percent, these shales are not considered as potential hydrocarbon source rocks (Tissot and Welte, 1978). Dutton (1987) suggested that the most likely sources for hydrocarbons in Travis Peak reservoirs in eastern Texas are laminated, lime mudstones of the lower member of the Jurassic Smackover Formation and prodelta and marine shales of the Bossier Shale, basal formation of the Cotton Valley Group (fig. 3). Sassen and Moore (1988) demonstrated that Smackover carbonate mudstones are a significant hydrocarbon source rock, charging various reservoirs in Mississippi and Alabama, and Wescott and Hood (1991) documented the Bossier Shale as a significant source rock in eastern Texas. Presley and Reed (1984) suggested that gray to black shales interbedded with Cotton Valley sandstones, as well as the underlying Bossier Shale, probably are the source for gas in Cotton Valley Sandstone reservoirs. Coleman and Coleman (1981) agreed with this interpretation for Cotton Valley sandstone reservoirs in northern Louisiana, stating that “hydrocarbons were generated from neighboring source beds.”

In summary, despite limited source-rock data, it seems likely that adequate hydrocarbon source rocks occur in the Bossier Shale immediately beneath Cotton Valley sandstones and also in stratigraphically lower Smackover carbonate mudstones (fig. 3).

## Burial and Thermal History

In a study of diagenesis and burial history of the Travis Peak Formation in eastern Texas, Dutton (1987) reported that measured vitrinite reflectance ($R_o$) values for Travis Peak shales generally range from 1.0 to 1.2 percent. This indicates that these rocks have passed through the oil window ($R_o$ = 0.6 to 1.0 percent) and are approaching the level of onset of dry-gas generation ($R_o$ = 1.2 percent) (Dow, 1978). A maximum $R_o$ of 1.8 percent was measured in the deepest sample from a downdip well in Nacogdoches County, Texas. Despite thermal maturity levels reached by Travis Peak shales, the small amount, and gas-prone nature, of organic matter in these shales precludes generation of oil, although minor amounts of gas might have been generated (Dutton, 1987).

In the absence of actual measurements of $R_o$, values of $R_o$ can be estimated by plotting burial depth of a given source-rock interval versus time in conjunction with an estimated paleogeothermal gradient (Lopatin, 1971; Waples, 1980). Dutton (1987) presented burial-history curves for tops of the Travis Peak Formation, Cotton Valley Group, Bossier Shale, and Smackover Formation for seven wells on the crest and western flank of the Sabine uplift. The burial-history curves show total overburden thickness through time and use present-day compacted thicknesses of stratigraphic units. Sediment compaction through time was considered insignificant because of absence of thick shale units in the stratigraphic section. Loss of sedimentary section associated with late, mid-Cretaceous and mid-Eocene erosional events was accounted for in the burial-history curves.

Dutton (1987) provided justification for using the average present-day geothermal gradient of 2.1°F/100 ft for the paleogeothermal gradient for the five northernmost wells. Paleogeothermal gradients in the two southern wells probably were elevated temporarily because of proximity to the area of initial continental rifting. Based on the crustal extension model of Royden and others (1980), Dutton (1987) estimated values for elevated paleogeothermal gradients for these two wells for 80 m.y. following the onset of rifting before reverting to the present-day gradient for the past 100 m.y.

Using estimated paleogeothermal gradients in conjunction with burial-history curves, Dutton (1987) found that calculated values of $R_o$ for Travis Peak shales agree well with measured values. Because of this agreement, Dutton (1987) used the same method to calculate $R_o$ values for tops of the Cotton Valley Group, Bossier Shale, and Smackover Formation in eastern Texas. Estimated $R_o$ values for the Bossier Shale and Smackover in seven wells range from 1.8 to 3.1 percent and 2.2 to 4.0 percent, respectively, suggesting that these rocks have reached a stage of thermal maturity in which dry gas was generated. Assuming that high-quality, gas-prone source rocks occur within these two formations, it is likely that one or both of these units generated gas found in overlying Cotton Valley and Travis Peak reservoirs.

No such regional source-rock and thermal-maturity analysis is known for Travis Peak and Cotton Valley intervals in northern Louisiana. Scardina (1981) presented burial-history data for the Cotton Valley Group, but included no information on geothermal gradients and thermal history of rock units. Present-day reservoir temperatures in tight Cotton Valley sandstones of eastern Texas and the tight, massive Terryville Sandstone in northern Louisiana both are in the 250°F to 270°F range (Finley, 1986; White and Garrett, 1992). It is likely that Bossier and Smackover source rocks in northern Louisiana experienced relatively similar thermal history to their stratigraphic counterparts in eastern Texas and, therefore, are sources for Cotton Valley gas in northern Louisiana. Herrmann and others (1991) presented a burial-history plot for Ruston field in the Cotton Valley blanket-sandstone trend in northern Louisiana. They suggested that Smackover gas was derived locally from Smackover lime mudstones and Cotton Valley gas from Cotton Valley and Bossier shales. Their burial-history plot shows the onset of generation of gas from Smackover and Bossier source rocks at Ruston field occurred about 80 Ma and 45 Ma, respectively. As noted above in this report, the Sabine uplift has been a positive feature for the past 60 m.y. (Kosters and others, 1989; Jackson and Laubach, 1991). Therefore, it would have been a focal area for gas migrating from Smackover, Bossier, and upper Cotton Valley source rocks in eastern Texas and northern Louisiana.

## Abnormal Pressures

Pore pressure or reservoir pressure commonly is reported as a fluid-pressure gradient (FPG) in pounds per square inch/foot (psi/ft). Normal FPG is 0.43 psi/ft in freshwater reservoirs and 0.50 psi/ft in reservoirs with very saline waters (Spencer, 1987). Abnormally high pore pressures as high as 0.86 psi/ft have been encountered in Cotton Valley reservoirs in northeastern Louisiana (fig. 9). Multiple FPG values for a particular gas field in figure 9 refer to gradients calculated for different, stacked blanket-sandstone reservoirs penetrated in that field. Across northern Louisiana, as shown in figure 9, the highest FPG's of 0.84 and 0.86 psi/ft occur in the southeast, and gradients generally decrease to nearly normal values of 0.43 to 0.50 psi/ft in the northwest. This pattern exhibits general agreement with reservoir-pressure data for northern Louisiana summarized by Coleman and Coleman (1981) (fig. 10). The dashed line in figure 10 shows a modification of Coleman and Coleman's (1981) pressure boundary to include the 0.63 psi/ft gradient in Hico-Knowles field and 0.67 psi/ft gradient in Tremont field (fig. 9). Most significant for this study, the boundary between overpressured and normally pressured Cotton Valley sandstones (fig. 10) shows no relationship to the two different productive Cotton Valley sandstone trends defined by differences in reservoir properties (fig. 8). Additionally, most Cotton Valley sandstone reservoirs, especially in the tight, massive-sandstone trend across northwestern Louisiana and eastern Texas are normally pressured, as shown in figure 9.

## History of Cotton Valley Group Sandstone Exploration

Beginning in 1937 and continuing through the early 1960's, commercial gas production was established from porous and permeable Cotton Valley Group blanket-sandstone reservoirs across northern Louisiana. Blanket sandstones flowed gas at commercial rates without artificial stimulation. Initial discoveries were in anticlinal traps associated with salt structures. Subsequent discoveries came from more complex and subtle traps, including (1) combination traps with blanket sandstones pinching out across anticlines or structural noses, and (2) stratigraphic traps with blanket sandstones pinching out on regional dip (Pate, 1963; Coleman and Coleman, 1981). By the early 1960's, the high-porosity blanket-sandstone play matured, and exploratory drilling waned. Low-porosity, low-permeability, Cotton Valley massive sandstones to the south in Louisiana and to the west on the Sabine uplift in northwestern Louisiana and eastern Texas flowed gas at rates less than 1,000 MCFD (thousand cubic feet of gas per day) and were not commercial with gas selling at $0.18/MCF in the 1960's (Collins, 1980).

In the 1970's, gas production from low-permeability, Cotton Valley massive sandstones became commercial as a result of technical advances in hydraulic-fracturing techniques together with significantly higher gas prices. At Bethany field on the Sabine uplift in eastern Texas in 1972, Texaco successfully increased the rate of production from tight Cotton Valley sandstones from 500 MCFD to a sustained rate of 2,500 MCFD and 30 BCPD (barrels of condensate per day) through hydraulic fracturing (Jennings and Sprawls, 1977). In conjunction with development of improved stimulation technology, price deregulation through the Natural Gas Policy Act (NGPA) of 1978 spawned a dramatic increase in drilling for gas in low-permeability Cotton Valley sandstones (Bruce and others, 1992). In 1980, the Federal Energy Regulatory Commission (FERC) officially classified low-permeability Cotton Valley sandstones as "tight gas sands," qualifying them for additional price incentives. Production from tight Cotton Valley sandstones surged. At Carthage field in eastern Texas, for example, production from Cotton Valley sandstones increased from 2.2 BCFG (billion cubic feet of gas) in 1976 to 70.9 BCFG in 1980 (Meehan and Pennington, 1982). The large area

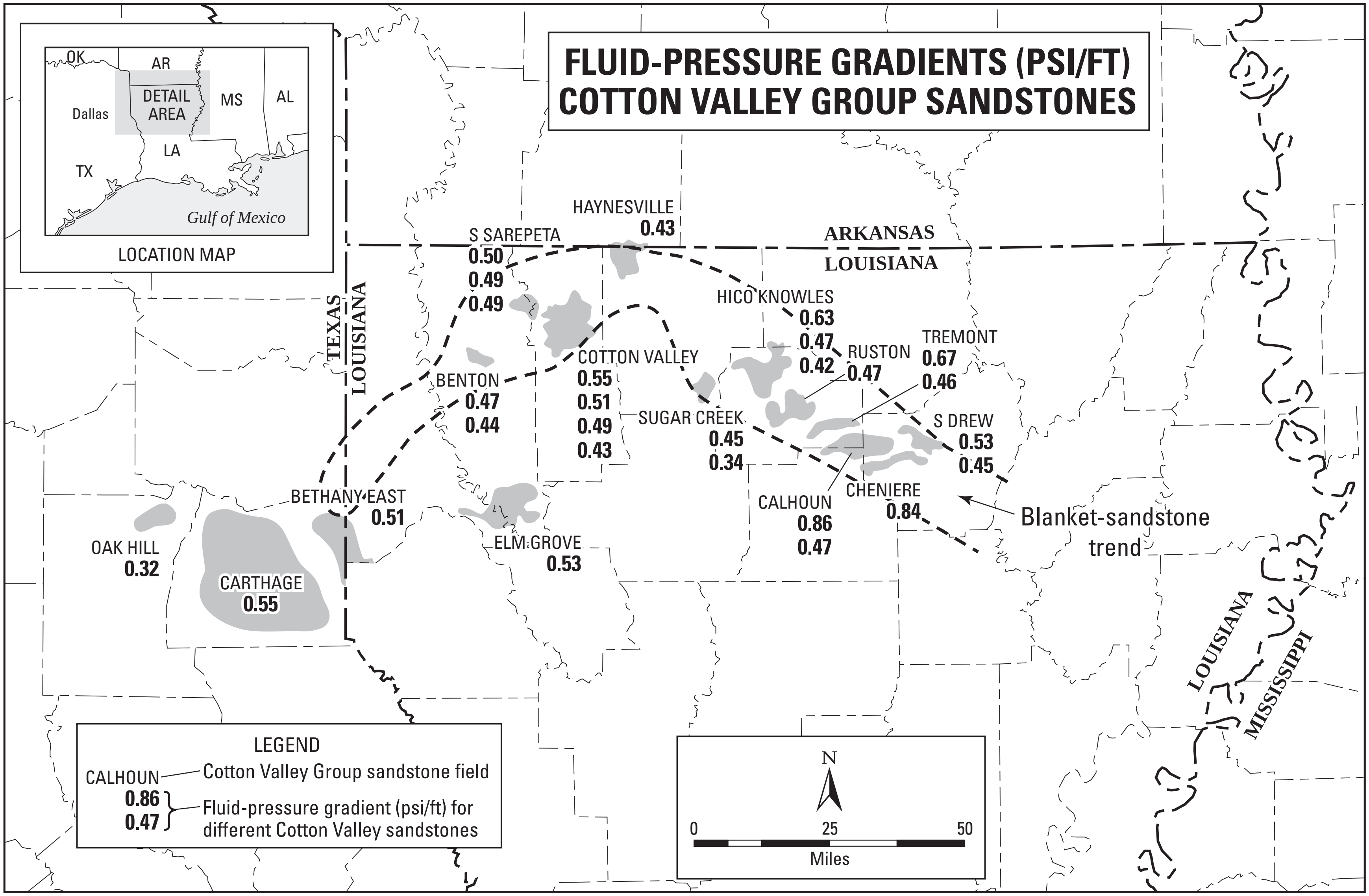



**Figure 9.** Map of northeastern Texas and northwestern Louisiana showing fluid-pressure gradients calculated from shut-in pressures in Cotton Valley Group sandstone reservoirs. Multiple pressure-gradient values for a particular gas field refer to gradients calculated for different, stacked blanket-sandstone reservoirs penetrated in that field. Shut-in-pressure data for Louisiana fields shown in table 2.

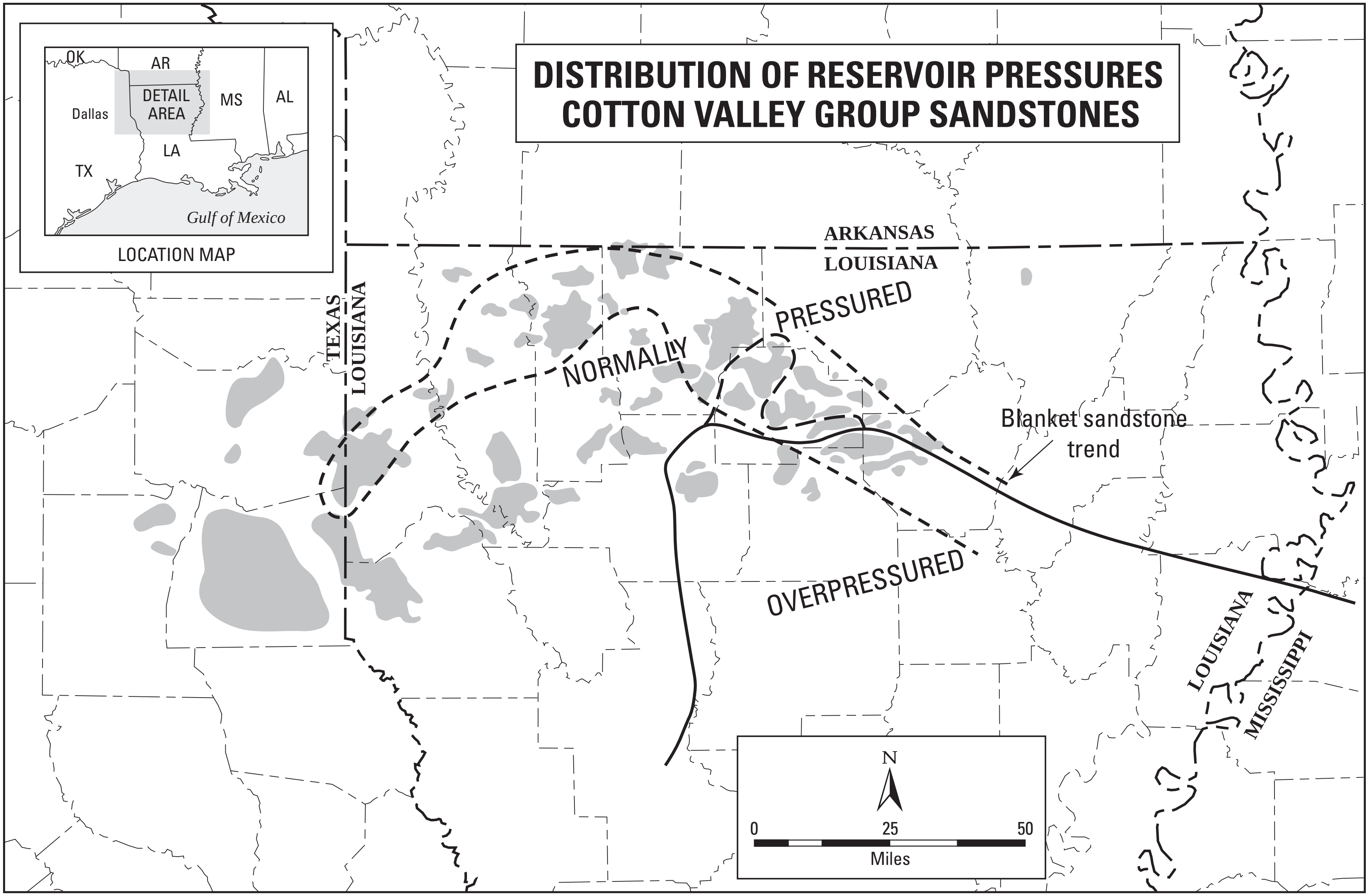



**Figure 10.** Map of northeastern Texas and northwestern Louisiana modified from Coleman and Coleman (1981) showing geographic distribution of abnormally high pressures in Cotton Valley Group sandstone reservoirs. Dashed line shows modification of Coleman and Coleman's (1981) pressure boundary to include the 0.63 psi/ft fluid-pressure gradient in Hico-Knowles field and 0.67 psi/ft gradient in Tremont field as shown in figure 9 and documented in table 2. Comparison of this map with map in figure 8 shows boundary between overpressure and normal pressure cuts across two productive trends of Cotton Valley sandstones.

across northern Louisiana and northeastern Texas within which Cotton Valley sandstones have been designated tight-gas sandstones by FERC includes all the counties identified by name on figure 4 (Dutton and others, 1993).

## Comparison of Blanket-Sandstone and Massive-Sandstone Trends

Two productive Cotton Valley sandstone trends are identified based on reservoir properties (fig. 8). As described above, Cotton Valley sandstone reservoir properties are a function of diagenetic characteristics, which are controlled primarily by variations in depositional environment. Reservoir properties, in turn, govern gas-production characteristics, including both initial rate of gas production and necessity of hydraulic-fracture treatments to achieve commercial production rates. Table 1 summarizes these and other key parameters distinguishing blanket- and massive-sandstone Cotton Valley reservoir trends. Data presented in table 1 were derived from a variety of sources as indicated in the table headnote, with much of the information coming from a series of reports by the Shreveport Geological Society on oil and gas fields in northern Louisiana (Shreveport Geological Society Reference Reports, 1946, 1947, 1951, 1953, 1958, 1963, 1980, 1987). Detailed information obtained from those reports on more than 20 Cotton Valley oil and gas fields in northern Louisiana, including data on porosity, permeability, initial production rates, gas-water contacts, and FPG's, is presented in table 2.

Most of the significant fields across northern Louisiana and northeastern Texas from which Cotton Valley sandstones produce gas are shown in figure 8. The area shown in figure 8 is part of the larger region shown in figure 4 within which Cotton Valley sandstones were designated as tight-gas sandstones by FERC in 1980. As shown in figure 8, however, 15 Cotton Valley fields were excluded from FERC's tight-gas sandstone designation. All but one of these fields are located within the porous and permeable Cotton Valley blanket-sandstone trend.

### Blanket-Sandstone Trend

Transgressive, Cotton Valley blanket sandstones have porosities ranging from 10 to 19 percent and permeabilities from 1 to 280 mD (tables 1 and 2). Porosity and permeability data are not readily available for all productive blanket sandstones in Cotton Valley fields. However, sufficient data are available from several blanket-sandstone reservoirs within a dozen fields across northern Louisiana to observe the widespread distribution of relatively high quality reservoir sandstones across the Cotton Valley blanket-sandstone trend (fig. 11). Data shown in figure 11 are derived primarily from field reports by the Shreveport Geological Society and from White and others (1992). Multiple values of porosity and permeability for a given field in figure 11 represent measured values for separate, stacked blanket-sandstone reservoirs within that field. Average porosity and permeability for Cotton Valley blanket sandstones, calculated from data in figure 11, are 15 percent and 110 mD, respectively.

The relatively high porosity and permeability of blanket sandstones is reflected in (1) the ability of these sandstones to flow gas and (or) liquids on open-hole DST's, and (2) high initial flow rates of gas from these sandstones in production tests without hydraulic-fracture stimulation treatments, as shown in figure 12. Multiple values of initial flow rates for a given field shown in figure 12 indicate rates from different stacked blanket sandstones that produce in that field. Across

**Table 1.** Comparison of two productive trends of Cotton Valley Group sandstones in eastern Texas and northern Louisiana.

[Data from Shreveport Geological Society (1946, 1947, 1951, 1953, 1958, 1963, 1980, 1987); Collins (1980); Nangle and others (1982); Finley (1984, 1986); Bebout and others (1992); and Dutton and others (1993). TSTM, too small to measure]

| Parameter | Blanket sandstone | Massive sandstone |
|---|---|---|
| Porosity (percent) | 10 to 19 (average = 15) | 6 to 10 |
| Permeability (mD) | 1.0 to 280 (average = 110) | 0.042 (E. Texas) 0.015 (N. Louisiana) |
| Open-hole DST | Wells flow gas and (or) liquids | Wells generally do not flow gas or liquids |
| Stimulation treatment | No treatment necessary for commercial production | Massive-hydraulic fracturing required to achieve commercial production |
| Initial flow rates (MCFD) | 500 to 25,000 (average 5,000) | Pre-stimulation: TSTM to 300<br>Post-stimulation: 500 to 2,500 |
| Sw in productive zones | < 0.40 | Can be as high as 0.60 |
| Gas/water contacts | Short, well-defined transition zones and gas-water contacts | Long transition zones with poorly defined gas-water contacts |
| Formation damage | Possible | Commonly severe |

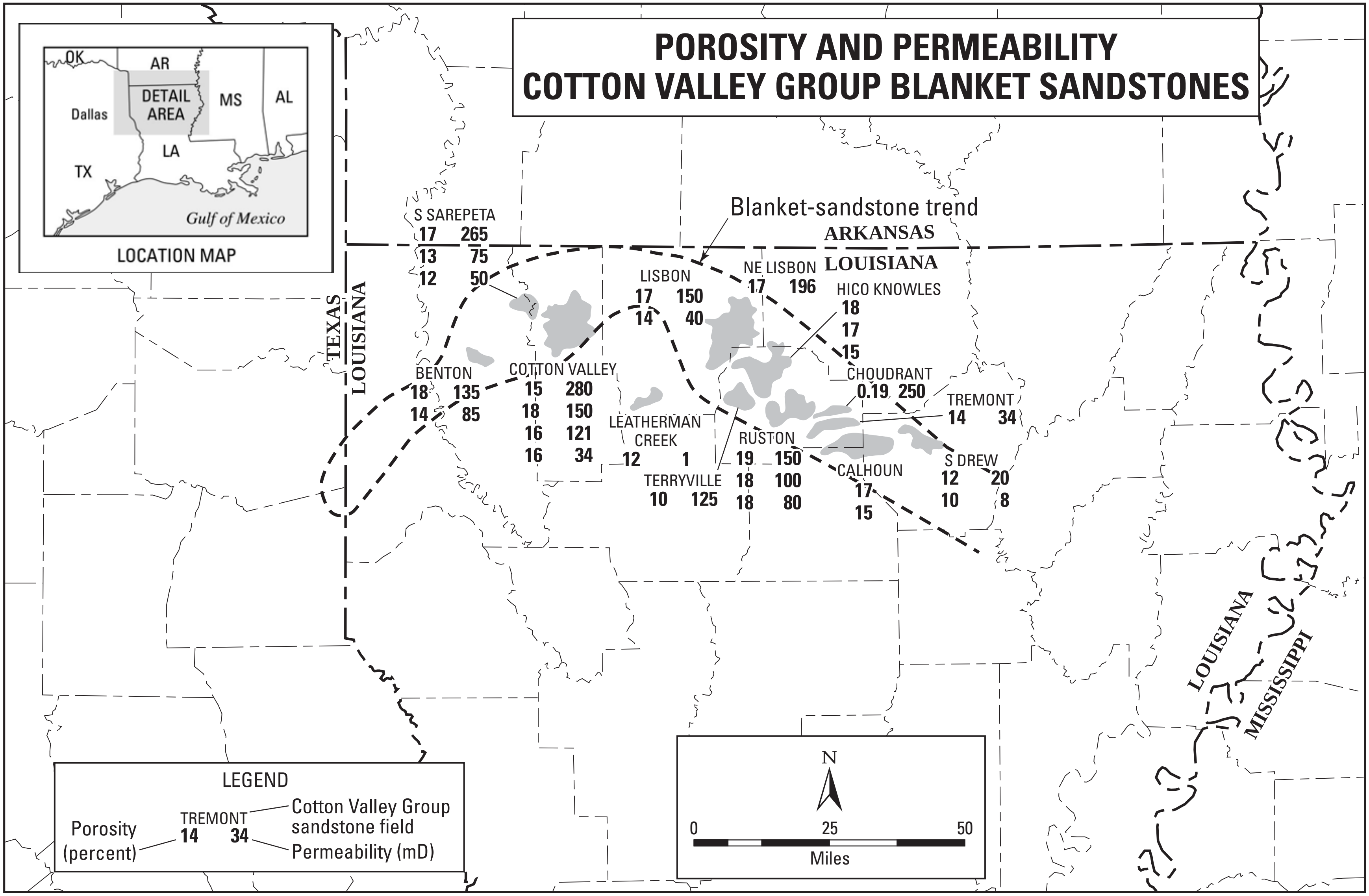



**Figure 11.** Map of northeastern Texas and northwestern Louisiana showing measured values of porosity and permeability in Cotton Valley Group blanket sandstones. Porosity and permeability data documented in table 2. Multiple values of porosity and permeability for a given field represent measured values for separate, stacked blanket-sandstone reservoirs in that field.

**Table 2.** Data on Cotton Valley Group sandstone fields in northern Louisiana.

[See end of table for explanation of abbreviations]

| Field | FERC "tight" | Trend | Trap | Disc date | CV disc date: ss | Depth CV perfs (ft) | IP (CV) (MCFD) | (BOPD) | (BCPD) | (BWPD) | GOR | Por (%) | Perm (mD) Avg | Min | Max | BHT (°F) | BHP (psi) | FPG (psi/ft) | Sw | GWC | Drive | SGS ref rpt (vol:pge) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ada-Sibley | Yes | M | Comb (FA, FC) | 1936 | 1954: CV | 9,900 | | | | | | | | | | | | | | | | I: 93; I: 189 |
| Athens | | B | Struct (FA) | 1941 | 1948: Vaughn | 8,500-8,544 | 10,500 | | 254 | | 41,338:1 | | | | | | | | | | | II: 385; III-2: 41; IV: 197 |
| | | | | | 1949: "B" | 8,464-8,494 | 12,000 | | 156 | | 76,923:1 | | | | | | | | | | | |
| | | | | | 1950:Bodcaw | 8,148-8,186 | 694 | | 2 | | 347,000:1 | | | | | | | | | | | |
| | | | | | 1951: "D" | 8,145-8,170 | 3,370 | | 208 | | 16,201:1 | | | | | | | | | | | |
| Bayou Middlefork | Yes | B | Struct (A) | | 1953: Bodcaw | 7,764 | 191 | 210 | | | 00,909:1 | | | | | | | | | | | |
| Bear Creek-Bryceland | Yes | M | Struct (A) | 1937 | 1966 CV | 10,700 | | | | | | | | | | | | | | | | I:97; V: 114 |
| Beekman | No | | Comb (N, FC) | 1942 | 1942: Cv | 3,700-3,711 | 1,500 | 35 | | 28 | 42,800:1 | | | | | | | | | | | II: 391 |
| Benton | Yes | B | Struct (A) | 1944 | 1944: "D" | 8,001-8,040 | 3,280 | | 164 | | 20,000:1 | 18 | 136 | | | 190 | 3,765 | 0.47 | 0.17 | GWC -7,818 | | II: 395; VII: 44 |
| | | | | | 1945: Bodcaw | 8,137-8,148 | 1,306 | 127 | | | 10,286:1 | 14 | 85 | | | 190 | 3,725 | 0.44 | | OWC -7,876 | | |
| Blackburn | Yes | B | Comb (N, FC) | 1953 | 1953: Bodcaw | 8,717 | 1,301 | | 54 | | 24,092:1 | | | | | | | | | | | |
| E. Blackburn | Yes | B | | 1959 | | | | | | | | | | | | | | | | | | |
| Cadeville | Yes | B | | 1955 | | 9,700 | | | | | | | | | | | | | | | | |
| Calhoun | No | B | Struct (FA) | 1948 | 1948: "D" | 9,500 | 814 | | 22 | | 37,000:1 | 17 | | | | | 4,000 | 0.47 | | | SG,PD | No SGS report |
| | | | Comb (FA, FC) | | 1957: Cadeville | 9,121-9,124 | 4,779 | | 1,148 | | 4,162:1 | 15 | | | 2,132 | | 8,201 | 0.86 | 0.05 | | SG,PD | Pate & Goodwin, 1961 |
| Carlton | Yes | B | Struct (A) | 1953 | 1953: Bodcaw | | | | | | | | | | | | | | | | | |
| N. Carlton | No | B | Comb (A,FC) | | 1964: Purdy | 8,950 | | | | | | | | | | | | | | | | No SGS report |
| | | | | | 1965: CV ? | 9,470 | | | | | | | | | | | | | | | | |
| Cartwright | Yes | B | | 1960 | | | | | | | | | | | | | | | | | | |
| Caspiana | Yes | M | Comb (N, FC) | | 1975: Cotton Valley | 8,500 | | | | | | | | | | | | | | | | |
| Cheniere | No | B | Comb (N, FC) | 1962 | 1962: Cadeville | 9,682-9,697 | 4,401 | | 528 | | 8,335:1 | | | | | | 8,188 | 0.84 | | | | v: 120 |
| | | | | | 1963: CV "A" | 9,603-9,609 | 1,230 | | 8 | | 153,750:1 | | | | | | | | | | | |
| Choudrant | Yes | B | Struct (A) | 1946 | 1946: "D" | 9,097--9129 | 4,732 | | 211 | | 21,000:1 | 19 | 250 | | | | | | | Separate GWCs in 2 "D" ss | | II: 409; III-2: 55 |
| Clay | Yes | M | Struct (A) | | 1952: CV | 9,700 | | | | | | | | | | | | | | | | No SGS report |
| Cotton Valley | No | B | Struct (A) | 1922 | 1937: Bodcaw | 8,170 TD (OH) | 5,323 | | 455 | | 11,700:1 | 16 | 121 | | 775 | 231 | 4,000 | 0.49 | 0.15 | GWC @ -8,420 | WD | II:413; VI:63 |
| | | | | | 1937: Davis | 8,521-8,551 (OH) | 4,800 | | 400 | | 12,000:1 | 15 | 280 | | | | 4,368 | 0.51 | 0.10 | | GC | |
| | | | | | 1938: "D" | 8,502-8,532 | 1,020 | 1,200 | | | 00,850:1 | 18 | 150 | | | | 3,926 | 0.43 | | | | |
| | | | | | 1949: Justiss | 9,050 | | | | | | 16 | 34 | | | | 4,700 | 0.55 | 0.22 | | GC | |
| | | | | | "C" | | | | | | | | | | | | | | | | | |
| | | | | | Taylor | | | | | | | | | | | | | | | | | |
| D'Arbonne | Yes | B | | 1947 | 1947: Bodcaw | 8,157 | 4,100 | | 88 | | 46,590:1 | | | | | | | | | | | |
| Dixie | Yes | B | | 1929 | | | | | | | | | | | | | | | | | | |
| Downsville | Yes | B | | 1948 | | | | | | | | | | | | | | | | | | |
| S. Downsville | No | B | Struct (A) | 1961 | 1961: Vaughn | 8,900 | | | | | | | | | | | | | | | | No SGS report |
| S. Drew | Yes | B | Strat (FC) | 1972 | 1972: "D" | 9,061-9,069 | 2,560 | | | | 85,000:1 | 12 | 20 | | | 200 | 4,850 | 0.53 | 0.40 | 3 GWCs in "D" ss | GC | VI: 116 |
| | | | | | 1976: Vaughn | 9,525-9,531 | 873 | | 15 | | 58,200:1 | 10 | 8 | | | 200 | 4,250 | 0.45 | 0.40 | | GC | |
| Elm Grove | Yes | M | Struct (FA) | | 1973 Cotton Valley | 7,768 | | | | | | 8 | 1 | | | 247 | 4,154 | 0.53 | 0.45 | | | |
| Greenwood-Waskom | No | B | | 1924 | | | | | | | | | | | | | | | | | | |
| Haynesville | Yes | B | Struct (A) | 1921 | 1944: Taylor | 8,835-8,920 | | 373 | | | 01068:1 | | | | | | 3,870 | 0.43 | | | | I: 119; III-1, 18 |
| | | | | | 1945: Camp | 7,980-8,004 | | 264 | | | 00500:1 | | | | | | | | | | | |
| E. Haynesville | Yes | B | | 1945 | 1949: Tucker | 8,588-8,600 | 2,898 | | 276 | | 10,500:1 | | | | | | | | | | | II: 435; III-2: 63 |
| Hico-Knowles | No | B | | | | | | | | | | | | | | | | | | | | |
| Hico | No | B | Struct (FA) | 1946 | 1946: Vaughn | 8,525-8,556 | 8,240 | | 121 | | 68,100:1 | 17 | | | | | 3,686 | 0.42 | | Multiple GWCs | PD | I:125; III-2: 75 |
| | | | | | 1946: Bodcaw | 8,287-8,345 | 892 | | 41 | | 21,649:1 | 18 | | | | | 4,061 | 0.47 | | | PD | |
| | | | | | 1949: Feazel-McFearin | 8,914-8,929 | 2,880 | | 308 | | 9,350:1 | 15 | | | | | 5,616 | 0.63 | | | | |
| Knowles | No | B | Struct (A) | 1945 | 1945: Vaughn | 8,700-8,750 | 5,212 | | 139 | | 37,500:1 | | | | | | 3,500 | 0.40 | | | | III-2: 82 |
| | | | | | 1946: Bodcaw | 8,630-8,670 | 8,516 | | 158 | | 53,900:1 | | | | | | | | | | | |
| | | | | | 1948: McCrary | 8,912-8,924 | 6,762 | | 761 | | 8,886:1 | | | | | | | | | | | |
| | | | | | 1953: Feasel-McFearin | 8,996-9,008 | 7,000 | | 275 | | 25,450:1 | | | | | | | | | | | |

**Table 2.** Data on Cotton Valley Group sandstone fields in northern Louisiana—*Continued*.

| Field | FERC "tight" | Trend | Trap | Disc date | CV disc date: ss | Depth CV perfs (ft) | IP (CV) (MCFD) | IP (CV) (BOPD) | IP (CV) (BCPD) | IP (CV) (BWPD) | GOR | Por (%) | Perm (mD) Avg | Perm (mD) Min | Perm (mD) Max | BHT (°F) | BHP (psi) | FPG (psi/ft) | Sw | GWC | Drive | SGS ref rpt (vol:pge) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Homer | Yes | M | | 1919 | | | | | | | | | | | | | | | | | | |
| Ivan | Yes | B | | 1952 | | | | | | | | | | | | | | | | | | |
| Lake Bistineau | Yes | M | | 1916 | | | | | | | | | | | | | | | | | | |
| Leatherman Creek | Yes | M | Struct (FA) | 1975 | 1975: Cotton Valley | 10,400-10,800 | | | | | | 12 | 1 | | | | | | 0.30 | | PD | VI: 70 |
| Lisbon | No | B | Struct (FA) | 1936 | 1939: Vaughn | 8,444-8,464 | 5,000 | | 61 | | 82,000:1 | 17 | 150 | | | | | | 0.35 | | PD | I: 143 |
| | | | | | 1940: Burgess-Simmons | 8,766-8,806 | 1,993 | | 160 | | 12,458:1 | 14 | 40 | | | | | | | | PD | |
| N. Lisbon | No | B | Comb (N, FC) | 1941 | 1942: Burgess-Simmons | 8,502-8,525 | 510 | | 17 | | 30,000:1 | | | | | | | | | | | I: 169 |
| | | | | | 1943: Bodcaw | 7,790-7,816 | 19,000 | | | | | 17 | 196 | | | | | | | | | |
| Longwood | Yes | M | Strat (FC) | 1927 | 1948: Bodcaw | 8,350 | | | | | | | | | | | | | | | | |
| Minden | Yes | M | | 1957 | | | | | | | | | | | | | | | | | | |
| Plain Dealing | Yes | M | | 1946 | | | | | | | | | | | | | | | | | | |
| Rocky Mount | Yes | B | | 1959 | | | | | | | | | | | | | | | | | | |
| Ruston | No | B | Comb (A,FC) | 1943 | 1948: "D" | 8,796-8,806 | 6,500 | | 56 | | 24,000:1 | 18 | 100 | | | 210 | 4,100 | 0.47 | 0.23 | GWC in Vaughn ss | PD | I: 185; III-2: 87; VI: 108 |
| | | | | | 1949: Bodcaw | 8,707-8,730 | 4,263 | | 195 | | 21,860:1 | 19 | 150 | | | | | | | | PD | |
| | | | | | 1949: Vaughn | 8,809-8,838 | 7,995 | | 390 | | 20,501:1 | | | | | | | | | | PD | |
| | | | | | 1949: "D" | 8,674-8,706 | 8,250 | | | | | | | | | | | | | | PD | |
| | | | | | 1949: Bodcaw | 8,760-8,810 | 15,500 | | | | | | | | | | | | | | PD | |
| | | | | | 1951: Feazel (Davis) | 9,468-9,476 | 1,062 | | 50 | | 21,240:1 | 18 | 80 | | | | | | | | PD | |
| S. Sarepta | Yes | B | Comb (FA,FC) | 1949 | 1949: Bodcaw | 8,710 | 2,160 | | 173 | | 12,485:1 | 17 | 265 | | | | 4300 | 0.49 | 0.14 | | PD | |
| | | | | | 1949: Savis | 9,000 | | | | | | 13 | 75 | | | | 4,500 | 0.50 | 0.15 | | PD | |
| | | | | | 1949: Ardis | 9,150 | | | | | | 12 | 50 | | | | 4,525 | 0.49 | 0.14 | | GC | |
| Sentell | No | B | Comb (N, FC) | 1951 | 1951: Bodcaw | 8,320 | 25,500 | | 455 | | 56,043:1 | 16 | 50 | | | | | | | | | No SGS report |
| Shongaloo | Yes | B | | 1921 | | | | | | | | | | | | | | | | | | |
| Sligo | No | M | | 1922 | | | | | | | | | | | | | | | | | | I: 193 |
| Sugar Creek | Yes | B | Struct (FA) | 1930 | 1957: Bodcaw | 8,724-8,730 | 5,000 | | 210 | | 23,810:1 | | | | | | 3,972 | 0.45 | | | | I: 213; VI: 126 |
| | | | | | 1957: Vaughn | 8,780-8,795 | 2,850 | | 48.5 | | 58,763:1 | | | | | | 2,955 | 0.34 | | | | |
| | | | | | 1958: "D" | 7,917-7,925 | 21,000 | | 896 | | 23,437:1 | | | | | | | | | | | |
| | | | | | 1962: "D" | 7,686-7,693 | 3,200 | | 112 | | 28,571:1 | | | | | | | | | | | |
| | | | | | 1962: McFearin | 8,003-8,008 | 2,800 | | 168 | | 17,500:1 | | | | | | | | | | | |
| | | | | | 1979: Price | 9,462-9,474 | 520 | | | | | | | | | | | | | | | |
| Terryville | No | B | Comb (N, FC) | 1954 | 1954: "D" | 9,203-9,227 | 3,739 | | 277 | | 13,514:1 | 10 | 125 | | | | | | | GWC in "D" ss | WD | V: 196 |
| | | | | | 1957: "C" | 9,169-9,182 | 1,030 | | 38 | 29 | 27,105:1 | | | | | | | | | | | |
| | | | | | 1959: "C" | 9,049-9,053 | | 133 | | | 00,934:1 | | | | | | | | | | | |
| | | | | | 1962: McGrary | 9,354-9,362 | 4,000 | | 300 | | 13,333:1 | | | | | | | | | | | |
| Tremont | Yes | B | Comb (N, FC) | 1944 | 1944: Bodcaw | 9,060-9,080 | 2,235 | | 97 | | 23,000:1 | | | | | | 4,200 | 0.46 | | | | I: 219; VI: 133 |
| | | | | | 1971: Davis | 9,633-9,706 | 1,145 | | 144 | | 7,951:1 | 14 | 34 | | | 217 | 6,519 | 0.67 | 0.15 | | PD | |
| Unionville | Yes | B | Strat (FC) | 1950 | 1950: Vaughn | 8,550 | | | | | | | | | | | | | | | | |
| | | | | | 1950: Davis | 8,700 | | | | | | | | | | | | | | | | |
| Vernon | Yes | M | Strat (FC) | | 1967: Cadeville | 10,900 | | | | | | | | | | | | | | | | |

Field — Name of field producing from Cotton Valley Group (CV) sandstone
FERC "tight" — Did FERC designate the field "tight-gas sand" for Cotton Valley Group?
Trend — B, Blanket-sandstone trend
M, Massive-sandstone trend
Trap — Trapping mechanism for field
Struct, structural trap
Strat, stratigraphic trap
Comb, combination structural & stratigraphic trap
A, anticline
FA, faulted anticline
FC, facies change (sandstone pinchout)
N, structural nose
Disc date — Discovery date of field
CV disc date: ss — Date of CV sandstone discovery and specific CV ss that was productive
Depth CV perfs — Depth in feet of CV perforations in discovery well for specific ss

IP (CV) — IP for specific CV ss
GOR — Gas:oil ratio
Por — Porosity (decimal)
Perm — Permeability (mD) [nonstressed]
BHT — Bottom hole temp (°F)
BHP — Bottom hole pressure (psi)
FPG — Fluid-pressure gradient (psi/ft)
Sw — Water saturation (decimal)
GWC — Information about gas-water contact
Drive — Drive mechanism
SG, solution gas
PD, pressure depletion
GC, Gas-cap expansion
WD, water drive
SGS ref report — Shreveport Geological Society Reference Report (vol: page)

the blanket-sandstone trend, as shown in figure 12, initial production rates range from 500 MCFD to 25,000 MCFD and average 5,000 MCFD.

Gas-water contacts have been reported from seven fields across the blanket-sandstone trend as shown in figure 13. In Hico-Knowles, South Drew, and Choudrant fields, separate gas-water contacts for individual blanket-sandstone reservoirs have been identified (table 2). No gas-water contacts were encountered in Cheniere field as of 1963 or in Tremont field as of 1980 (table 2). In all other Cotton Valley fields described in Reference Reports by the Shreveport Geological Society (1946, 1947, 1951, 1953, 1956, 1963, 1987), no mention of fluid contacts was made.

## Massive-Sandstone Trend

Cotton Valley sandstones in the massive-sandstone trend (fig. 8 and table 1) have significantly poorer reservoir properties than those in the blanket-sandstone trend. Massive Cotton Valley sandstones have sufficiently low permeability that they generally do not flow gas or liquids during open-hole DST's, and they require fracture-stimulation treatment to obtain commercial rates of gas production (Collins, 1980). Commercial gas production from these sandstones was not achieved until technological advances in hydraulic fracturing occurred together with higher gas prices from deregulation in the 1970's. Consequently, development of Cotton Valley fields in the tight, Cotton Valley massive-sandstone trend did not occur until the late 1970's and 1980's. Cotton Valley development drilling in Elm Grove and Caspiana fields in northern Louisiana continues at the time this report is being written (Al Taylor, Nomad Geosciences, oral commun., April 2000). A consequence of such recent development of fields in the tight, Cotton Valley massive-sandstone trend is less published information on characteristics of these fields than on older fields in the blanket-sandstone trend.

### Limited Data in Published Literature

Summary information presented by Dutton and others (1993) for the tight, Cotton Valley massive-sandstone trend across northeastern Texas and northern Louisiana indicates porosities in the 6- to 10-percent range. Based on measurements from cores in 11 wells in Carthage field, one of the largest Cotton Valley fields in northeastern Texas, Wilson and Hensel (1984) reported porosities ranging from 5.8 to 8.1 percent, with an average of 6.6 percent. Associated permeabilities range from 0.02 to 0.33 mD, with an average of 0.067 mD. From core data for 126 wells in Harrison and Rusk counties in northeastern Texas, Finley (1984) reported an average permeability of 0.042 mD for Cotton Valley sandstones. In northern Louisiana, average permeability was reported as 0.015 mD based on data from Cotton Valley cores in 302 wells. However, there are stratigraphic intervals within the tight, Cotton Valley massive-sandstone trend with significantly higher permeabilities. Locally, permeabilities approaching 100 mD have been reported (Wilson and Hensel, 1984).

Significantly lower porosity and permeability of tight, Cotton Valley massive sandstones relative to blanket sandstones is reflected in poorer production characteristics. The average flow rate prior to fracture-stimulation treatment is 50 MCFD (Dutton and others, 1993). Post-stimulation rates generally are in the 500 to 2,500 MCFD range, although rates as high as 10,000 MCFD and 11,700 MCFD have been reported from Bethany field (Jennings and Sprawls, 1977) and Carthage field (Meehan and Pennington, 1982), respectively.

There are few published data on presence of gas-water contacts or production of water without gas on the flanks of Cotton Valley fields in the tight, massive-sandstone trend. Summary data presented by Nangle and others (1982) described gas-water contacts as poorly defined with long transition zones in contrast to short, well-defined transition zones with sharp gas-water contacts in the blanket-sandstone trend. Dutton and others (1993) also suggested the presence of gas-water contacts with long transition zones by indicating that calculated water saturations should be less than 40 percent to achieve successful gas completions from Cotton Valley sandstone intervals 200 ft above the free-water level.

In northeastern Texas, where most of the drilling for tight Cotton Valley sandstones has occurred, the best reservoir potential is reported to be in wave-dominated deltaic sandstones of the Taylor sandstone in the lower part of the Cotton Valley interval (Wescott, 1983, 1985). In Oak Hill field, production logs show that Taylor sandstones contribute more than 80 percent of the gas production and that sandstones in the middle and upper Cotton Valley section contribute most of the water production, although they produce significant gas as well (Tindall and others, 1981). Presley and Reed (1984) and Dutton and others (1993) both report the presence of water-bearing sandstones in the upper Cotton Valley interval. To avoid production of water from these sandstones, fracture-stimulation treatments in stratigraphically adjacent gas-bearing sandstones in the upper Cotton Valley must be significantly smaller than those in the Taylor sandstone. At Bethany field, several wells reportedly were plugged because of production of salt water from Cotton Valley sandstones (Jennings and Sprawls, 1997).

### Analysis of Drill-Stem-Test and Production-Test Data

As mentioned above, general statements in published reports suggest the presence of gas-water contacts in fields that produce gas from tight Cotton Valley sandstones across northeastern Texas and northern Louisiana. Unlike data for the Cotton Valley blanket-sandstone trend, however, no documentation was found identifying specific gas-water contacts in Cotton Valley sandstones in any of the tight-gas-sandstone fields in Texas or Louisiana. In the absence of such published data, and

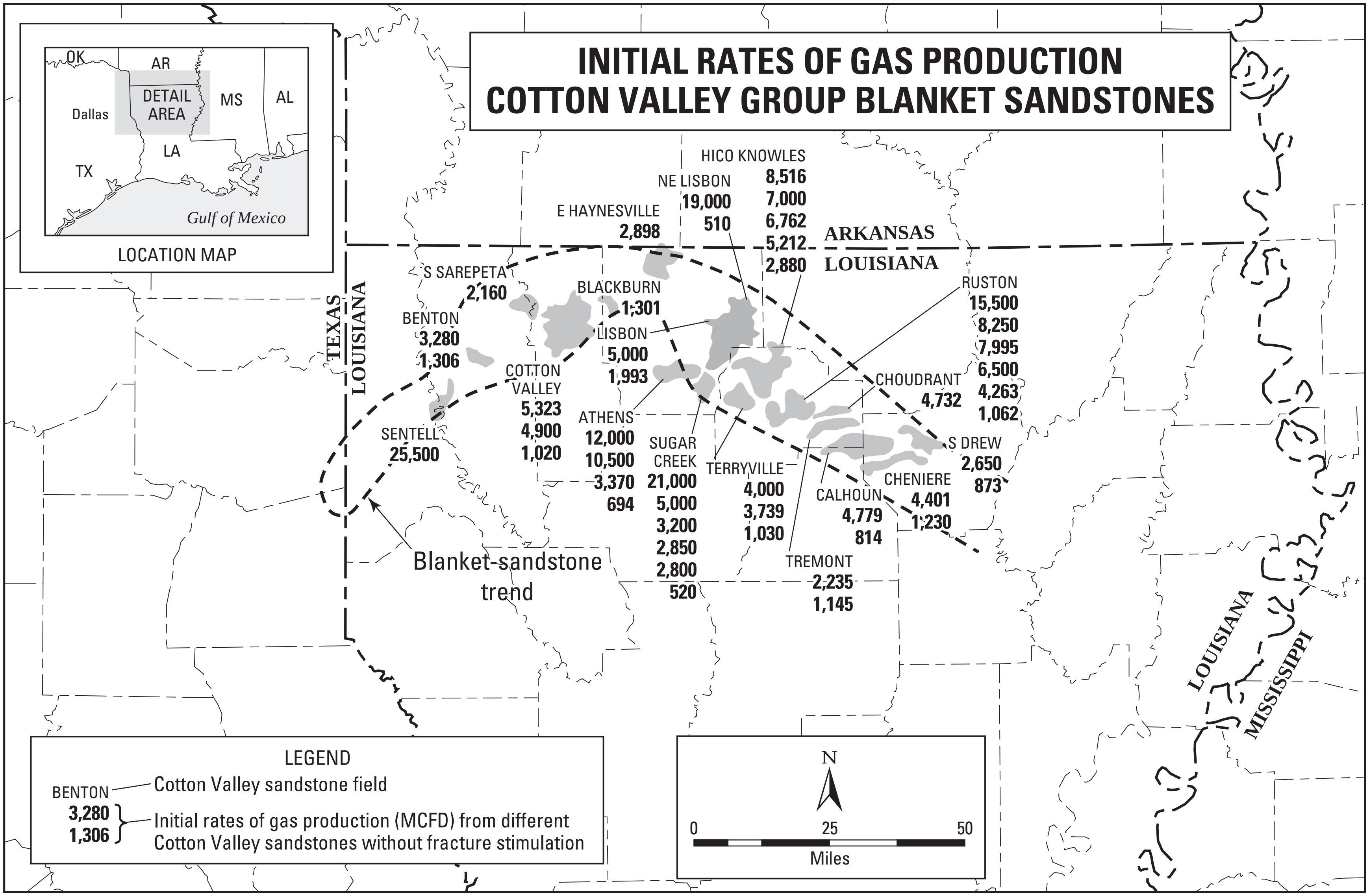



**Figure 12.** Map of northeastern Texas and northwestern Louisiana showing initial rates of gas production from Cotton Valley Group blanket sandstones. Multiple values of initial flow rates for a given field represent rates from different stacked blanket-sandstone reservoirs that produce in that field. All rates are from blanket sandstones, which do not require fracture-stimulation treatment for commercial production.

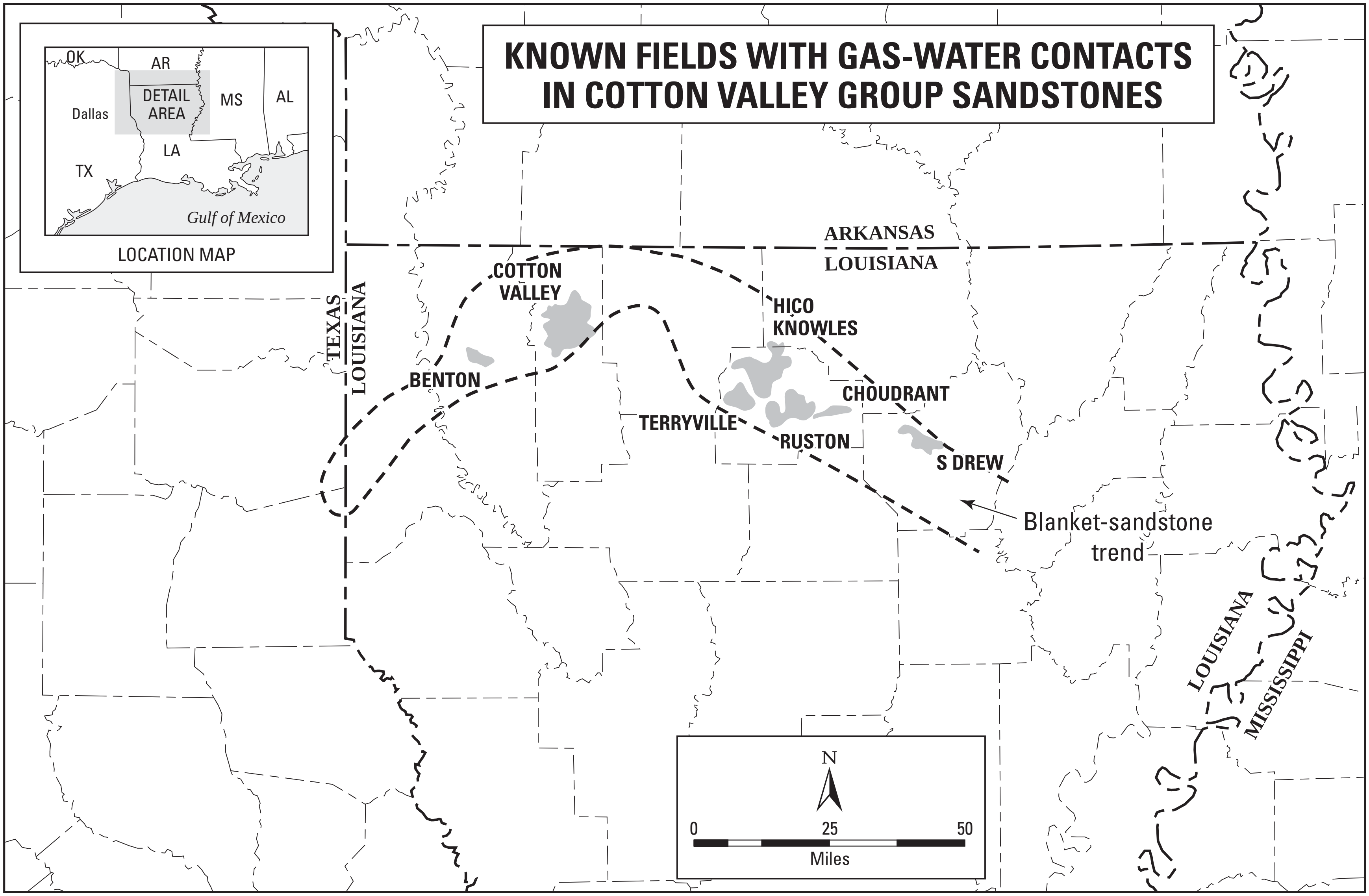



**Figure 13.** Map of northeastern Texas and northwestern Louisiana showing fields productive from Cotton Valley Group sandstones in which gas-water contacts have been identified and reported in published literature. Presence of gas-water contacts in these fields suggests that they are conventional gas accumulations. Details on gas-water contacts, including sources of information, are shown in table 2.

considering the difficulties of using wireline logs to evaluate water saturations in tight Cotton Valley sandstones, an attempt was made to document the presence or absence of gas-water contacts through analysis of data from DST's and production tests. The goal was to determine if Cotton Valley fields that produce from tight-gas sandstones are flanked by dry holes that tested water without gas, suggesting presence of a gas-water contact. A data set of wells penetrating the Cotton Valley Group across most of northeastern Texas and northern Louisiana was extracted from a database (PI/Dwights Plus, a trademark of Petroleum Information/Dwights, d.b.a. IHS Energy Group) for analysis of DST and production-test data using ArcView software. Because tight Cotton Valley sandstones generally do not flow fluids on open-hole DST's, it was anticipated that the most useful data would be derived from production tests made through perforations in casing following fracture-stimulation treatments. Well data were sorted and displayed in map view using ArcView software such that wells that produce from Cotton Valley sandstones could be distinguished from dry holes with tests. While viewing the map display, test results from any particular well could be examined.

Reconnaissance analysis of data from Carthage, Bethany, Oak Hill, Waskom, and Woodlawn fields in northeastern Texas and from Bear Creek–Bryceland, Elm Grove, and Caspiana fields in northern Louisiana revealed few dry holes penetrating Cotton Valley strata on the flanks of these Cotton Valley fields. No flanking dry holes were found that tested only water. The few Cotton Valley dry holes present generally did not report tests, suggesting that no tests were performed in those wells and that, most likely, the wells were plugged based on evaluation of wireline logs.

Test results from Cotton Valley sandstones in Oak Hill field in Texas and Elm Grove–Caspiana fields in Louisiana were evaluated more rigorously, revealing several general patterns. Initial rates of gas production generally are higher in crestal wells than in flank wells in these fields, as shown for Caspiana field in figure 14. At both Oak Hill and Elm Grove–Caspiana fields, initial rates of gas production from Cotton Valley sandstones range from 1,000 to more than 4,000 MCFD in central parts of the fields and generally are less than 1,000 MCFD in structurally lower wells on edges of the fields. Many flank wells exhibit initial rates of less than 500 MCFD, as shown in figure 14. This trend exhibits more variability at Oak Hill field, where a larger number of low-rate wells occur in the center of the field. Such low-rate wells in the central part of the field could be attributed to a number of factors, including reservoir variability, formation damage during drilling, and poor fracture-stimulation treatments. All these wells must be fracture stimulated, and significant variation in success of such stimulation treatments is not uncommon. Also, initial rates on the western flank of Oak Hill field are high and show an abrupt change to dry holes rather than a gradual decline toward the flank of the field. One well there flowed gas with an initial rate exceeding 4,000 MCFD and is flanked to the west by four Cotton Valley dry holes. In three of these dry holes, Cotton Valley sandstones apparently were not tested, and a test in the fourth well must have resulted in noncommercial production with only "one unit of gas" reported.

Initial rates of water production in BWPD (barrels of water per day) also were mapped at Oak Hill and Elm Grove–Caspiana fields and show no obvious patterns across these fields. No attempt was made to contour water production data for several reasons. Not only is variability in initial rate of water production high and seemingly random, but also, data are incomplete. Whereas the IHS Energy database reports initial rate of gas production for most all wells in these fields, initial rate of water production is not reported for a significant percentage of wells. In wells at Oak Hill or Elm Grove–Caspiana fields, for which a value is entered in the appropriate position of the database for water production, a null value is never reported. Some volume of water production seems to occur along with gas in all these wells. Hence, it does not seem appropriate to interpret absence of water-production data for a given well as meaning zero production of water. Absence of data on initial water production is more prevalent for Oak Hill field, and that factor alone makes it difficult to analyze water production from that field. Data on initial water production at Elm Grove–Caspiana fields are more complete. Although initial rates of water production were considerably higher at Caspiana field, data were more complete for that field, and patterns of initial water production at Caspiana field were evaluated by plotting barrels of water produced per MMCFG (bbl water/MMCFG). As shown in figure 15, wells in the central part of Caspiana field commonly exhibit production of 100 or fewer bbl water/MMCFG. Progressing outward toward flanks of the field, rates of initial water production increase to 300 bbl water/MMCFG and eventually to more than 600 bbl water/MMCFG. The highest initial rate of water production occurs in a well on the western flank of the field where production of 1,477 bbl water/MMCFG is reported (fig. 15). That same well had an initial rate of gas production of only 325 MMCFD, as shown in figure 14. Nevertheless, no wells that tested water only without gas from Cotton Valley sandstones were identified on the flanks of Caspiana field to suggest the presence of a gas-water contact for the field. Twenty-one Cotton Valley dry holes were identified surrounding Elm Grove–Caspiana fields. Of these, 19 wells reported no tests in the Cotton Valley sandstone interval, presumably indicating that no Cotton Valley tests were run and that Cotton Valley completions were made on the basis of wireline-log evaluation. Production tests after fracture-stimulation were run in two other wells. One reported "one unit of gas and one unit of oil," presumably indicating noncommercial rates. The other well reported only "one unit of water," suggesting that the Cotton Valley sandstone might be below a gas-water contact at that location. On the southern and western flanks of Oak Hill field, six Cotton Valley dry holes without tests were identified, again suggesting abandonment of Cotton Valley potential based on wireline-log evaluation. Production tests were run in Cotton Valley sandstones in two wells on the western flank of Oak Hill field. One reported "one unit of gas," the other "one unit of gas and one unit of water."

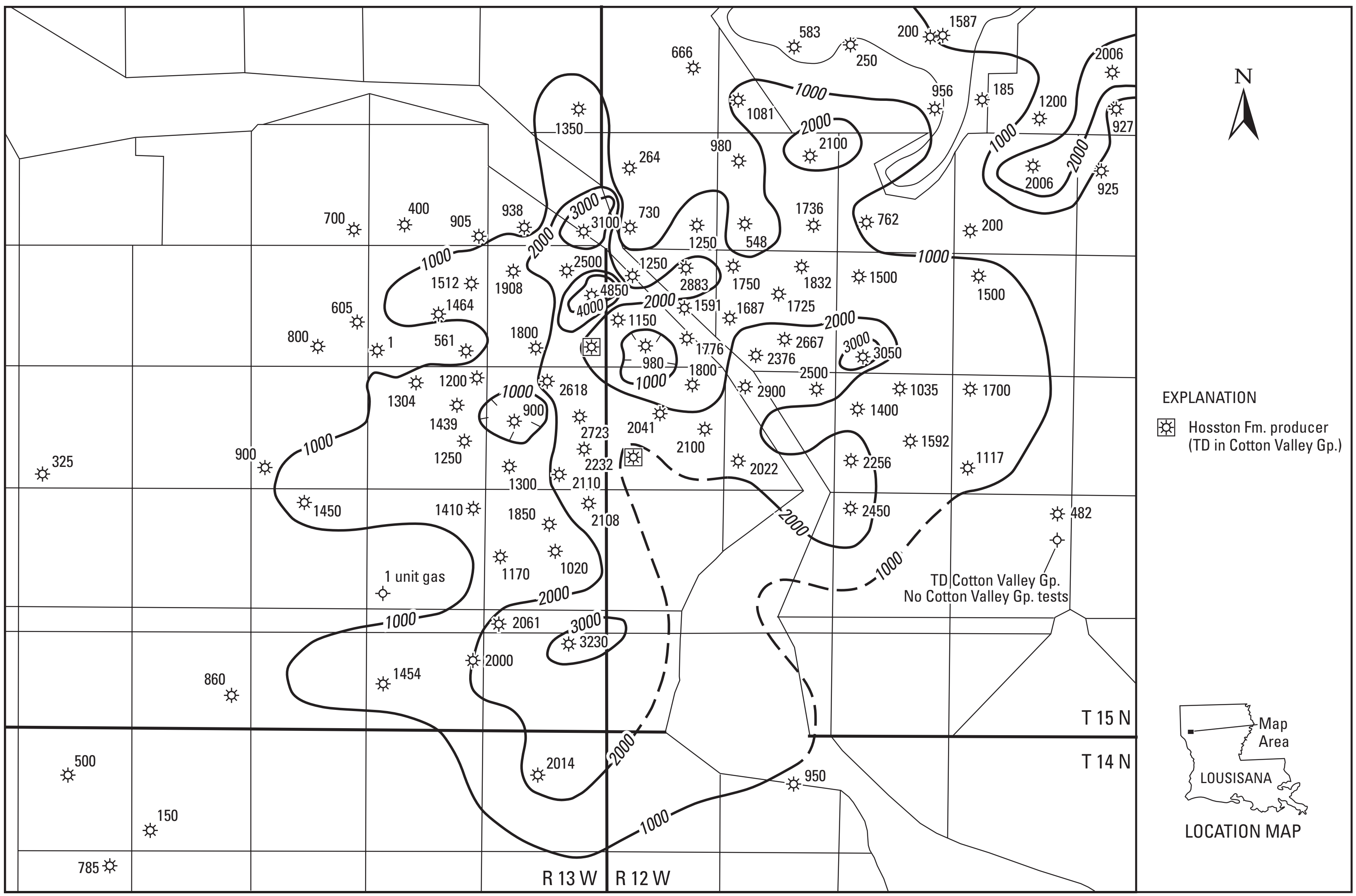



**Figure 14.** Map of Caspiana field in northwestern Louisiana in the tight, Cotton Valley Group massive-sandstone trend showing initial rate of gas production (MCFD) from Cotton Valley sandstone reservoirs. Data from PI/Dwights Plus, a trademark of Petroleum Information/Dwights, d.b.a. IHS Energy Group. Contour interval is 1,000 MCFD. Map shows general decrease in initial rates of gas production from center to flanks of field.

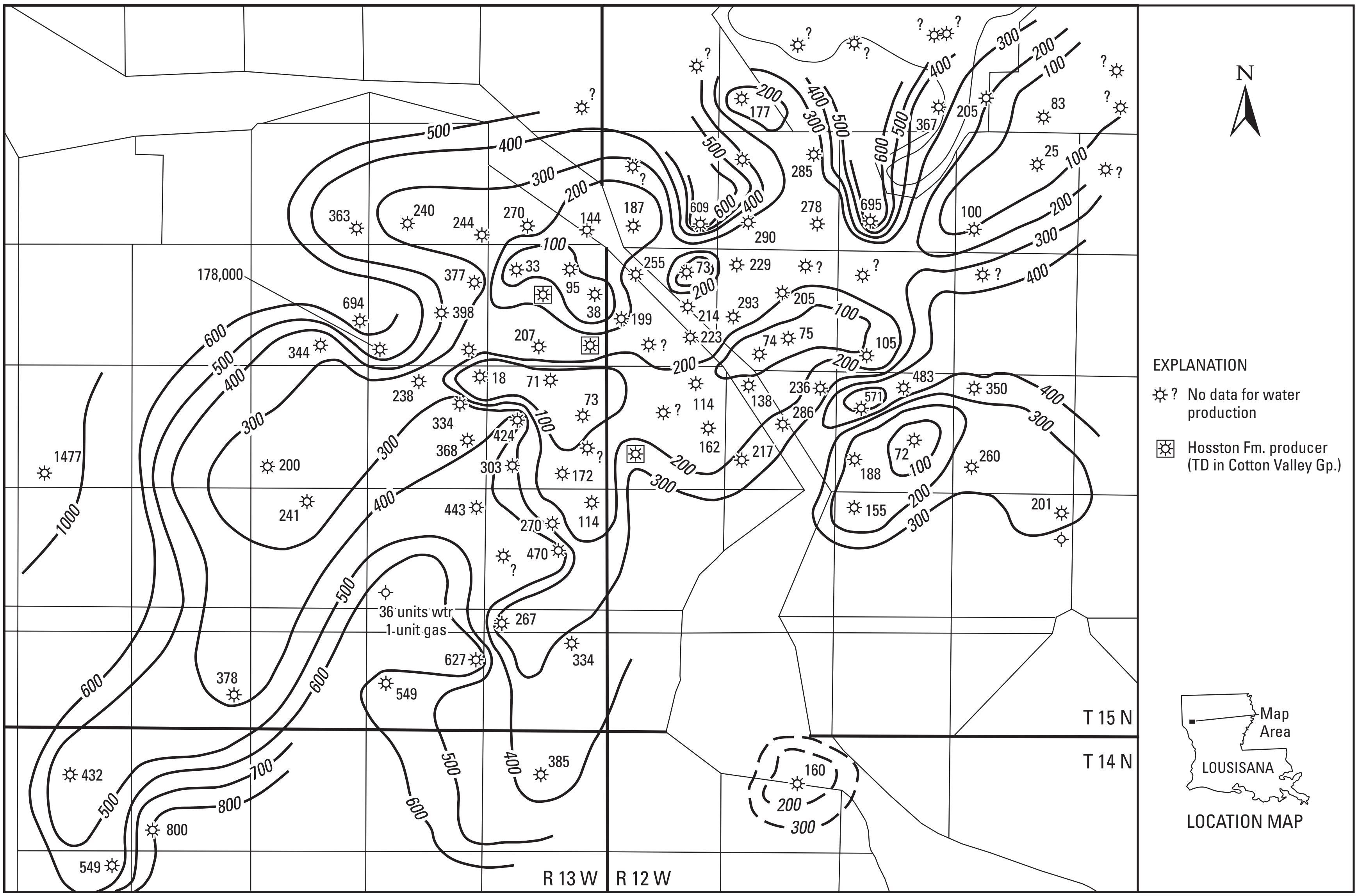



**Figure 15.** Map of Caspiana field in northwestern Louisiana in the tight, Cotton Valley Group massive-sandstone trend showing ratio of initial production rate of water (BWPD) to initial production rate of gas (MMCFGD) from Cotton Valley Group sandstones. Data from PI/Dwights Plus, a trademark of Petroleum Information/Dwights, d.b.a. IHS Energy Group. Contour interval is 100 BWPD/MMCFGD. Mapped data show progressive increase in ratio of initial production rates of water to gas from crest to flanks of field. This suggests that, within reservoir sandstones, gas saturation is decreasing and water saturation is increasing from crest to flanks of field and indicates presence of vertically extensive gas-water transition zone.

On the southern flank of the field, production tests were run in Cotton Valley sandstones in two Cotton Valley dry holes, but no results were reported. Evaluation of test data from Oak Hill and Elm Grove–Caspiana fields, therefore, provides no definitive information regarding presence or absence of gas-water contacts in these Cotton Valley fields.

# Discussion of Evidence For and Against Basin-Centered Gas

## Source Rocks and Burial and Thermal History

Source rocks responsible for generating gas in basin-centered gas accumulations commonly are in stratigraphic proximity to low-permeability reservoirs that they are charging with gas. As described above, there are few published data on source rocks responsible for generating gas found in Cotton Valley sandstone reservoirs in both the blanket- and massive-sandstone trends. However, the marine Bossier Shale, stratigraphically directly beneath Cotton Valley sandstones, and Smackover laminated lime mudstones, lying below the Bossier Shale, are considered to be source rocks capable of generating gas for Cotton Valley sandstone reservoirs. Gray to black marine shales interbedded with Cotton Valley sandstones also are considered to be potential source rocks. Also, as summarized above, burial- and thermal-history data for the northern Gulf Coast Basin suggest that burial depths of Bossier and Smackover source rocks, in conjunction with the regional geothermal gradient, have been sufficient to generate dry gas. Time of generation of much of the gas postdates development of both the Sabine uplift and structures in the East Texas and Louisiana Salt Basins. Hence, available data on presence of source rocks, burial and thermal history of source rocks, and timing of gas generation for Cotton Valley reservoirs would be consistent with interpretation of a potential continuous gas accumulation in massive sandstones of the Cotton Valley Group.

## Porosity, Permeability, and Gas-Production Rates

Basin-centered gas accumulations commonly involve large volumes of gas-saturated rock in which gas cuts across stratigraphic units. Such gas accumulations require a regional seal to trap gas, and that seal characteristically is provided by inherent low permeability of reservoir rocks themselves. Thus, continuous gas reservoirs characteristically have low permeability, and when reservoirs are sandstones, they commonly are referred to as tight-gas sandstones.

As described above, Cotton Valley sandstone reservoirs across the northern Gulf of Mexico Basin can be divided into two groups based on reservoir properties and associated rates of gas production. Sandstones in the Cotton Valley blanket-sandstone trend across northernmost Louisiana have porosities in the 10 to 19 percent range and permeabilities from 1 to 280 mD (table 1). These sandstones generally flow gas and (or) liquids during open-hole DST's. Gas-productive sandstones flow at initial rates ranging from 500 to 25,000 MCFD without fracture-stimulation treatment. Consequently, these sandstones are not tight-gas reservoirs, and many fields producing from Cotton Valley sandstones in the blanket-sandstone trend were excluded from tight-gas status by FERC in 1980 (fig. 8). Therefore, in the absence of some other regional top seal that could allow development of basin-wide overpressure, sandstones in this trend would not be expected to host a basin-centered gas accumulation.

South of the blanket-sandstone trend in northern Louisiana lies the Cotton Valley massive-sandstone trend that extends westward across the Sabine uplift into northeastern Texas, as shown in figure 8. Cotton Valley massive sandstones generally have porosities in the 6 to 10 percent range with permeabilities commonly less than 0.1 mD. Most of these sandstones, therefore, would be defined as tight-gas sandstones, and most fields producing gas from these sandstones were designated as tight-gas-sandstone fields by FERC in 1980. Tight, Cotton Valley massive sandstones generally do not flow gas and (or) liquids on open-hole DST's, and they require hydraulic-fracture treatment to produce gas at commercial rates. As shown in table 1, prestimulation initial-production rates generally range from too small to measure (TSTM) to 300 MCFD. Post-stimulation rates commonly are 500 to 2,500 MCFD. Although higher permeability intervals occur locally within the massive-sandstone trend, as noted by Wilson and Hensel (1984), the characteristic low permeability of sandstones throughout this trend suggests that they might have potential to provide their own seal for gas in a continuous gas accumulation.

## Abnormal Pressures

In a study of abnormally high pressures in basin-centered gas accumulations in Rocky Mountain basins, Spencer (1987) considered reservoirs to be significantly overpressured if FPG's exceed 0.50 psi/ft where waters are fresh to moderately saline, and 0.55 psi/ft where waters are very saline. With formation-water salinity of Cotton Valley sandstone reservoirs on the order of 170,000 ppm TDS (Dutton and others, 1993), salinity is considered high, and reservoirs should be considered to be overpressured if their FPG's exceed 0.55 psi/ft.

Based on Spencer's (1987) cutoff value of 0.55 psi/ft, abnormally high reservoir pressures have been encountered in Cotton Valley sandstones in an area of northeastern Louisiana, shown in figure 10, where calculated pressure gradients of 0.63 to 0.86 psi/ft occur. The boundary between areas of overpressure and normal pressure cuts across the permeable, blanket- and tight, massive-sandstone trends such that overpressures occur within both reservoir trends. (figs. 8 and 10). Although overpressures associated with generation of gas might be anticipated in tight Cotton Valley sandstones, such overpressures would not be expected to develop in high-permeability blanket sandstones without a subregional top seal stratigraphically above the sandstones. As shown in figure 9 and table 2, some of the separate, stacked blanket sandstones within Hico, Tremont, and Calhoun fields are overpressured, whereas others are normally pressured. Examination of discovery dates of gas in individual sandstones shows that, in all cases for these three fields, normally pressured sandstone reservoirs were discovered prior to overpressured ones. Thus, pressure differences among individual blanket-sandstone reservoirs indicate presence of separate, compartmentalized reservoirs rather than pressure depletion from production of gas from different sandstones that are in pressure communication. Additionally, normally pressured Cotton Valley sandstones were encountered at South Drew field, whereas, at Cheniere field immediately to the west, Cotton Valley sandstones were significantly overpressured with an FPG of 0.86 psi/ft. Thus, for gas fields in the blanket-sandstone trend where data are abundant, reservoir pressures exhibit significant variation from normal to abnormally high among separate sandstone reservoirs within individual gas fields and also between adjacent fields. Such compartmentalization of overpressured reservoirs in proximity to normally pressured ones, rather than development of overpressure on a regional scale, is more indicative of conventional gas fields than basin-centered gas accumulations.

Within the western half of the blanket-sandstone trend and spanning the vast majority of the tight, massive-sandstone trend across northwestern Louisiana and northeastern Texas, FPG's range from 0.32 to 0.55 psi/ft and, therefore, would be considered normal, according to the methodology of Spencer (1987). However, two episodes of erosion have occurred in northeastern Texas, one in late mid-Cretaceous time and the second in early mid-Tertiary time (Dutton, 1987; Laubach and Jackson, 1990; Jackson and Laubach, 1991). During late mid-Cretaceous time, maximum erosion occurred on the crest of the Sabine uplift where approximately 1,800 ft of sedimentary section were removed. Tertiary erosion resulted in removal of about 1,500 ft of section across much of northeastern Texas. Burial-history data for the Ruston field area in northern Louisiana on the boundary between overpressured and normally pressured regions, show about 1,500 and 500 ft of uplift and loss of section, respectively, in two erosional periods (Hermann and others, 1991). It is possible, therefore, that, with deeper burial, reservoir pressures in much or all of the massive-sandstone trend could have been higher and that pressure reduction has occurred as a result of uplift and erosion. However, some of the gas found in Cotton Valley sandstone reservoirs could have been derived from Bossier Shale source rocks. Migration of most of that gas into Cotton Valley sandstones probably commenced between 57 and 45 Ma (Dutton, 1987; Hermann and others, 1991). Therefore, if basin-wide overpressure in Cotton Valley sandstones were to have developed in response to thermal generation of gas from Bossier Shale source rocks, its development would have postdated both the Cretaceous and Tertiary erosional events.

The sharp boundary between overpressured and normally pressured areas of Cotton Valley sandstones (fig. 10) and presence of overpressure in both permeable, blanket-sandstone and tight, massive-sandstone trends, suggest that abnormally high pressures encountered in Cotton Valley sandstones in northeastern Louisiana are not caused by thermal generation and migration of gas. Coleman and Coleman (1981) attributed development of overpressures in Cotton Valley sandstones across the region shown in figure 10 to a late stage of diagenesis in which extreme pressure, presumably overburden pressure, and temperature caused dissolution of silica at contact points of quartz-sand grains and precipitation of silica in adjacent pores. With pore waters apparently unable to escape, porosity reduction associated with this late-stage chemical compaction reportedly resulted in development of overpressure in Cotton Valley sandstones across the area shown in figure 10. According to Coleman and Coleman (1981), a significant factor in preventing fluid loss from Cotton Valley sandstones during this late diagenetic episode was presence of a tight top seal provided by the Knowles Limestone and upper Cotton Valley–lower Hosston shales.

If late-stage chemical compaction and cementation in conjunction with a top seal of tight limestone and shale are responsible for development of overpressure, it is not clear why the geographic distribution of overpressure exhibits the pattern shown in figure 10. Perhaps an alternative mechanism for generating the distribution of overpressures within Cotton Valley sandstones shown in figure 10 could be one reported by Parker (1972) as the cause for overpressures in Jurassic Smackover sandstone and carbonate reservoirs to the east in Mississippi. Parker (1972) noted that much of the Smackover gas is sour and has a relatively high content of $CO_2$ and (or) $N_2$. He suggested that migration of gases derived from Late Cretaceous emplacement of the Jackson (igneous) dome (fig. 2) might be responsible for "inflation" of pressures in well-sealed Smackover reservoirs. Specifically, Jones (1977) suggested that $H_2S$ and $CO_2$ present in Smackover gas in Mississippi were derived from Smackover anhydrite and limestone/dolomite, respectively, which had been subjected to magmatic intrusion. The mapped pattern of overpressured Cotton Valley sandstones (fig. 10) extends east-southeastward into Mississippi directly toward the location of Jackson dome (fig. 2) (Studlick and others, 1990). Evidence supporting such a mechanism of overpressure development in Cotton Valley sandstones of northeastern Louisiana would be documentation of elevated levels of $CO_2$ and (or) $N_2$ in overpressured Cotton Valley sandstone reservoirs.

In summary, within most of the tight, Cotton Valley massive-sandstone trend across northwestern Louisiana and northeastern Texas, Cotton Valley reservoirs are slightly, but not significantly, overpressured. Based on the methodology and terminology of Spencer (1987), these reservoirs would be characterized as normally pressured. Basin-centered, continuous gas accumulations commonly are significantly overpressured. Although pressure data for the tight, Cotton Valley massive-sandstone trend are not definitive, they tend to suggest that a basin-centered gas accumulation characterized by abnormally high pressures from geologically recent to present-day thermal generation of gas does not occur within Cotton Valley sandstone reservoirs.

## Gas-Water Contacts

Perhaps the most definitive criterion for establishing the presence of a continuous gas accumulation is absence of gas-water contacts. Gas-water contacts are distinctive features of conventional gas accumulations. Presence of a gas-water contact indicates a change from gas-saturated to water-saturated porosity within a particular reservoir unit. This implies that a well drilled into that reservoir structurally below the gas-water contact should encounter only water, thereby demonstrating the absence of a continuous gas accumulation in that immediate area.

Within the blanket-sandstone trend across northernmost Louisiana, gas-water contacts have been reported in seven fields, as shown in figure 13. Because of relatively high porosity and permeability in blanket sandstones, gas-water contacts are sharp and often are reported as depth below sea level to the nearest foot. Separate gas-water contacts for individual, stacked blanket sandstones have been identified in Hico-Knowles, South Drew, and Choudrant fields (table 2). The seven fields in which gas-water contacts have been described are distributed across the blanket-sandstone trend (figure 13). Because of the relatively uniform distribution of high-permeability Cotton Valley sandstone reservoirs with conventional shale seals in fields across the blanket-sandstone trend, it is likely that all Cotton Valley fields in this trend have well-defined gas-water contacts similar to those documented in the seven fields shown in figure 13. The Cotton Valley blanket-sandstone trend was defined as a continuous gas accumulation in the 1995 National Assessment of United States Oil and Gas Resources by the USGS (Schenk and Viger, 1996). However, the presence of abundant gas-water contacts across this area suggests that the blanket-sandstone trend should be redefined as a conventional gas play.

Evaluating the presence or absence of gas-water contacts in the tight, Cotton Valley massive-sandstone trend is more difficult. No reference to specific gas-water contacts for Cotton Valley massive sandstones in any Cotton Valley gas field has been found in the published literature. Nangle and others (1982) and Dutton and others (1993), however, make general statements indicating that gas-water contacts are present in Cotton Valley fields across the tight, Cotton Valley massive-sandstone trend.

Although Taylor sandstones in the lower part of the Cotton Valley section produce gas in all significant Cotton Valley fields in the tight, massive-sandstone trend, water-bearing sandstones have been reported along with gas-charged sandstones in the middle and upper Cotton Valley interval in some fields. The seal for gas in wave-dominated deltaic Taylor sandstones at Waskom field reportedly is provided by marsh and lagoonal shales (CER Corporation and S.A. Holditch & Associates, 1991). This seal would be considered conventional rather than one provided by the low permeability of the reservoir sandstones. Along with Taylor sandstones, most of the upper Cotton Valley sandstone interval produces gas at some fields, such as Carthage field, according to Al Brake (BP, oral commun., 2000). At other fields, such as Woodlawn and Blocker, however, gas is produced only from lower Cotton Valley Taylor sandstones and from a few sandstones in the uppermost Cotton Valley section. Intervening middle and upper Cotton Valley sandstones are reportedly water-bearing. The presence of individual gas-bearing and water-bearing sandstone intervals, separated by conventional shale seals, suggests the presence of gas-water contacts and is more indicative of conventional gas accumulations than of continuous gas accumulations.

The complex diagenetic mineralogy of tight Cotton Valley sandstones probably precludes use of wireline logs to identify gas-water contacts. As reported above, complex diagenetic mineralogy of tight Cotton Valley sandstones dramatically affects values of resistivity and porosity measured by wireline logs and, hence, the determination of water saturation by standard calculation techniques. Because of vertical and lateral diagenetic variations, accurate determination of water saturation is difficult without accompanying lithologic data from cores or cuttings to calibrate wireline logs. Examination of production-test data from wells flanking many Cotton Valley gas fields in the tight-gas-sandstone trend reveals no dry holes that tested water without gas. Therefore, even if wireline logs provided accurate estimates of water saturations in tight Cotton Valley sandstones, few wells apparently exist in which logs could be used to identify gas-water contacts.

Reconnaissance evaluation of DST and production-test data from Cotton Valley sandstones in a number of fields in the tight-gas-sandstone trend revealed few dry holes penetrating Cotton Valley sandstones on flanks of those fields. No dry holes were found that tested water without gas, thereby implying existence of a gas-water contact for a particular field. Likewise, detailed examination of test data from all wells within and flanking Oak Hill and Elm Grove–Caspiana fields in the tight-gas-sandstone trend revealed no flank dry holes that tested water without gas.

Initial rates of gas production from wells on the flanks of Cotton Valley fields in the tight-gas, massive-sandstone trend, however, generally are lower than from crestal wells, as illustrated for Caspiana field in figure 14. Also, as shown for Caspiana field in figure 15, the ratio of initial rate of water production to initial rate of gas production in terms of bbl water/MMCFG is significantly higher in flank wells. Initial rates of gas production from crestal wells commonly range from 1,000 to more than 4,000 MCFD and the ratio of initial rate of water to gas generally is less than 200 bbl water/MMCFG and often below 100 bbl water/MMCFG (figs. 14 and 15). Initial rates of gas production from flank wells generally are less than 1,000 MCFD, and water production initially is significantly higher, usually in the 300 to 600 bbl water/MMCFG range,

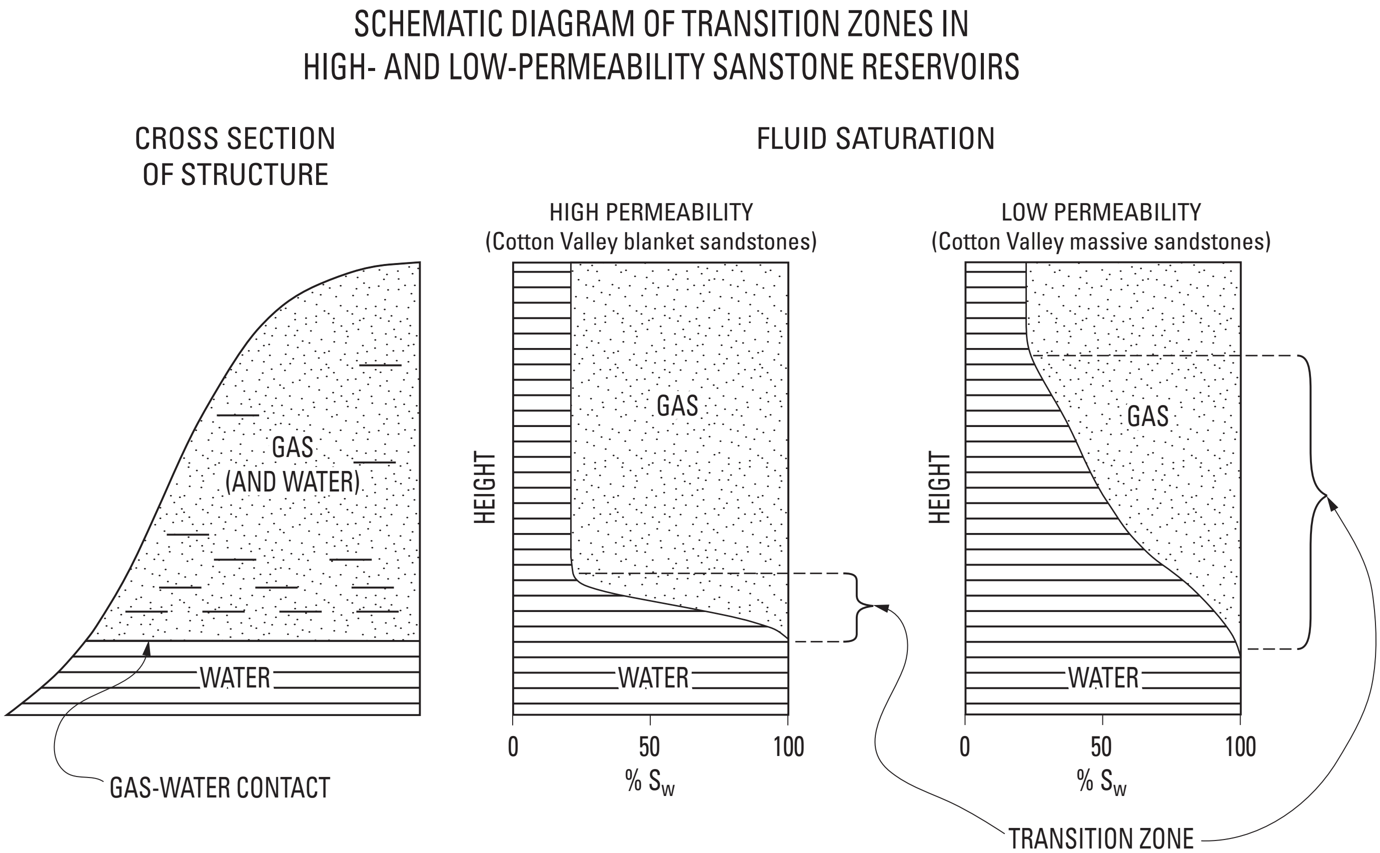



**Figure 16.** Schematic diagram of gas-water transition zones in high- and low-permeability reservoirs. Modified from Levorsen (1967).

but sometimes exceeding 1,000 bbl water/MMCFG (figs. 14 and 15). These data suggest a decrease in gas saturation and an accompanying increase in water saturation in Cotton Valley sandstones from crestal wells to flank wells and that a commercial limit to gas production has been reached, although gas-water contacts have not been encountered.

Corroborating these suggestions from figures 14 and 15 and data reported by Nangle and others (1982) is the experience of Al Taylor (Nomad Geosciences, oral commun., 2000) who reports the presence of vertically extensive gas-water transition zones in Cotton Valley sandstone fields in the massive-sandstone trend. In moving structurally lower from the crest of one of these tight-gas Cotton Valley fields through the long gas-water transition zone toward the presumed gas-water contact, gas saturation of sandstone reservoirs continually decreases while water saturation simultaneously increases (fig. 16). Wells that are low in the transition zone on the edges of Cotton Valley fields in the tight-gas-sandstone trend exhibit low initial rates of gas production and high initial rates of water production, as shown by some flank wells at Caspiana field in figures 14 and 15. Hyperbolic decline rates of gas production in conjunction with lower gas saturations of reservoir sandstones in these transition-zone wells result in such low cumulative production of gas that these wells are marginally commercial to noncommercial and, in effect, are dry holes (Al Taylor, Nomad Geosciences, oral commun., 2000). Hence, commercial limits of gas production are reached before gas-water contacts can be encountered by development drilling. This probably could be documented by mapping cumulative gas production or estimated ultimate gas recovery from wells in these Cotton Valley fields.

Knowing gas saturations of Cotton Valley reservoir sandstones from log calculations and capillary properties of those sandstones from core analyses at Caspiana field in northwestern Louisiana, Al Taylor (Nomad Geosciences, oral commun., 2000) estimated gas-column heights required to produce those gas saturations. From column-height data, he determined the position of gas-water contacts below sea level. Estimates made in this fashion for the structural level of the gas-water contact at Caspiana field using data from a number of wells cluster within a zone about 75 ft thick, suggesting the presence of a single gas-water contact for the field. A Cotton Valley well situated structurally below this estimated gas-water contact reportedly tested water without gas from Cotton Valley sandstones. Because of the vertically extensive gas-water transition zones present in fields producing gas from tight Cotton Valley sandstones in the massive-sandstone trend, Al Taylor (Nomad Geosciences, oral commun., 2000) suggests that structural or stratigraphic traps with less than 150 ft of vertical closure will not have sufficient gas saturation to produce gas at commercial rates.

In summary, Cotton Valley blanket sandstones across northernmost Louisiana have sufficiently high porosity and permeability that gas accumulations exhibit short transition zones and have sharp gas-water contacts. Gas fields in this trend have clearly defined productive limits, beyond which wells produce water only. However, low-permeability Cotton Valley sandstones in the tight-gas massive-sandstone trend across northern Louisiana, the Sabine uplift, and East Texas Basin display long gas-water transition zones with poorly defined gas-water contacts. Productive limits of fields in this trend are difficult to define based on data from production tests or wireline logs. In conjunction with long gas-water transition zones, structural dips are gentle on the flanks of these gas accumulations. As development drilling progresses down the flank of one of these fields through the long gas-water transition zone, gas saturations in the sandstone reservoir decrease and water saturations increase. Eventually gas saturations become sufficiently low that, in terms of ultimate cumulative gas production, wells become marginally commercial to noncommercial at a structural position still within the transition zone above the gas-water contact. Consequently, development wells on the flanks of these gas accumulations generally have not encountered gas-water contacts. If drilling and completion costs hypothetically were reduced to zero, causing even the smallest amount of gas recovery to be commercial, development drilling could progress down the full length of transition zones, and gas-water contacts probably would be encountered. The progressive increase in water saturation with depth within these tight-gas Cotton Valley fields, therefore, suggests that poorly defined gas-water contacts are present below the depth at which wells become noncommercial. The presence of gas-water contacts in both Cotton Valley blanket- and massive-sandstone trends suggests that gas accumulations in these trends are conventional and that a basin-centered gas accumulation does not exist within Cotton Valley sandstones in the northern Gulf of Mexico Basin.

## Basin-Centered Gas Potential within Bossier Shale

A basin-centered, continuous-gas accumulation might have been discovered recently in sandstones within the Bossier Shale, the lower formation of the Cotton Valley Group. In a currently developing play on the western flank of the East Texas Basin, gas is being produced from turbidite sandstones within the Bossier Shale. These turbidite sandstones probably are downdip time-equivalent deposits of deltaic sandstones in the lower portion of the Cotton Valley and reportedly were deposited seaward of the underlying Haynesville Formation carbonate platform edge in a slope or lowstand-fan setting. Accommodation space was provided by salt withdrawal such that updip and lateral traps currently are formed by pinch out of sandstone into shale. Two stacked, stratigraphically separate Bossier turbidite-fan systems reportedly occur at depths of 13,000 to 14,000 ft. Two fields, Dew and Mimms Creek, with combined estimated recoverable reserves of more than one TCFG, currently are being developed by Anadarko Petroleum, one of the main operators. As of January 2000 (PI-Dwights Drilling Wire, Jan 3, 2000; Jan 12, 2000), Anadarko had drilled more than 100 wells with only one dry hole in this Bossier sandstone play. Gas-charged sandstones reportedly are overpressured, and no water has been encountered in the system (Exploration Business Journal, 2nd quarter, 2000). Within the upper turbidite-fan interval, porosity ranges from 6 to 15 percent and permeability from 0.01 to 1.0 mD. Initial production rates from wells average 3 to 4 MMCFGD after fracture stimulation and decline exponentially with estimated per-well recoveries of 1 to 5 BCFG. In the lower sandstone interval, porosity ranges from 9 to 20 percent, permeability from 1 to 10 mD, pressures are higher, and initial production rates of as much as 30 MMCFGD have been obtained. This play does not seem to involve the classic type of basin-centered gas accumulation with the trap produced by inherent low permeability of reservoir sandstones. Instead, the trap seems to be provided by marine shales that completely encase these turbidite sandstones, but the sandstone reservoirs are overpressured, seem to lack water and gas-water contacts, and are gas-charged over an extensive area, as demonstrated by only one dry hole in more than 100 wells drilled.

## Conclusions

1. The Cotton Valley Group represents the first major influx of clastic sediment into the Gulf of Mexico Basin. Major depocenters were located in south-central Mississippi, along the Louisiana-Mississippi border, and in northeastern Texas. Sands supplied by the ancestral Mississippi River drainage along the Louisiana-Mississippi border were swept westward by longshore currents, creating an east-west barrier-island or strandplain system across northern Louisiana that isolated a lagoon to the north. More than 1,000 ft of stacked barrier-island sands accumulated as the Terryville massive-sandstone complex. Periodic transgressive events reworked barrier-island sands, transporting them northward into the lagoon. These transgressive sandstones pinch out into lagoonal shales, can be correlated across northern Louisiana, and are referred to informally as blanket sandstones.
2. Two major Cotton Valley sandstone-reservoir trends are identified based on reservoir properties and associated characteristics of gas production. Transgressive, blanket sandstones across northernmost Louisiana have porosities ranging from 10 to 19 percent and permeabilities from 1 to 280 mD. These sandstones flow gas and (or) liquids during open-hole DST's and do not require fracture-stimulation treatment to produce gas at commercial rates. Fields producing from these

sandstone reservoirs were developed during the 1940's through 1960's. Cotton Valley massive sandstones to the south, and extending westward across the Sabine uplift into eastern Texas, exhibit porosities from 6 to 10 percent and permeabilities generally less than 0.1 mD. Designated as tight-gas sandstones by FERC, these reservoirs commonly do not flow gas or liquids during DST's, and they require fracture-stimulation treatments to achieve commercial rates of production. Gas production from these sandstones in eastern Texas and northern Louisiana was not established until the mid 1970's when advances in hydraulic-fracture techniques occurred in conjunction with a significant increase in gas prices as a result of price deregulation.

3. Porosity and permeability of Cotton Valley sandstones are controlled by diagenetic properties, which in turn are governed by depositional environment. Although diagenetic patterns and mineralogy are complex, high-energy, clean sandstones generally are cemented by authigenic quartz and (or) calcite and have poor reservoir properties. In lower energy sandstones, clay coatings on quartz grains inhibited development of quartz overgrowths, resulting in preservation of primary porosity. High clay content, however, generally imparts poor permeability to these sandstones. The best reservoir sandstones are those which have experienced development of significant secondary porosity from dissolution of calcite cement and unstable framework grains.
4. The complex diagenetic mineralogy of tight Cotton Valley sandstones precludes use of standard calculation methods in reservoir evaluation with wireline logs. Bound water associated with pore-filling clays or clay coatings and conductive minerals such as pyrite result in abnormally low resistivity measurements leading to such high calculated water saturations that productive zones often appear wet. Also resulting in erroneous reservoir evaluations are pessimistic measurements of porosity with wireline logs caused by the presence of high-density carbonate minerals such as ankerite and siderite. Therefore, without lithologic data from cores or drill cuttings to calibrate wireline logs, such logs are of limited value in differentiating between gas-productive and wet intervals and therefore are of limited value in identifying gas-water contacts on the flanks of Cotton Valley fields.
5. Abnormally high reservoir pressures with fluid-pressure gradients exceeding 0.55 psi/ft occur in Cotton Valley sandstones in northeastern Louisiana. The boundary between the overpressured area on the east and normally pressured region to the west cuts across the permeable, blanket- and tight, massive-sandstone trends such that overpressures occur within both reservoir trends. Within the blanket-sandstone trend, where pressure data are more abundant, some Cotton Valley fields are overpressured whereas adjacent fields are normally pressured. Also, within certain fields, some of the stacked blanket sandstones are overpressured whereas others are normally pressured. Such compartmentalization of overpressured reservoirs in proximity to normally pressured ones, rather than development of overpressure on a regional scale, suggests that these blanket-sandstone fields are conventional gas accumulations and not part of a basin-centered gas accumulation. Also, the occurrence of normally pressured reservoirs across the majority of the tight, Cotton Valley massive-sandstone trend is not indicative of presence of a basin-centered, continuous gas accumulation. Geographic distribution of overpressures in Cotton Valley sandstones suggests that overpressuring was caused by "inflation" of existing pressures in tightly sealed reservoirs by gases derived from emplacement of the nearby Jackson (igneous) dome.
6. Gas found in Cotton Valley sandstone reservoirs is believed to be derived from (1) interbedded Cotton Valley marine shales, (2) underlying marine shales of the Bossier Shale, and (or) (3) stratigraphically lower, Jurassic Smackover laminated, lime mudstones. These source rocks are believed to have been buried to sufficient depths relative to the regional geothermal gradient to have generated dry gas during the past 60 m.y. Timing of gas generation and migration is favorable because it postdates development of the Sabine uplift, smaller structures on and flanking the uplift, and salt structures in the East Texas and Northern Louisiana Salt Basins. Stratigraphic proximity of source rocks to Cotton Valley sandstone reservoirs and appropriate thermal maturity and time of generation and migration would be consistent with interpretation of a potential basin-centered gas accumulation.
7. Presence of a gas-water contact is perhaps the most definitive criterion suggesting that a gas accumulation is conventional rather than a "sweetspot" within a basin-centered, continuous gas accumulation. Within the Cotton Valley blanket-sandstone trend across northernmost Louisiana, short gas-water transition zones and well-defined gas-water contacts have been reported in seven gas fields. Relatively high porosity and permeability of blanket sandstones and associated high gas-production rates achieved without fracture stimulation throughout the trend suggest that all gas fields within the blanket-sandstone trend probably have well-defined gas-water contacts; therefore, these gas accumulations are conventional.
8. Within the tight, massive-sandstone trend, porosity and permeability are sufficiently low that gas-water transition zones are long and gas-water contacts poorly defined. Productive limits of these tight-gas-sandstone Cotton Valley fields are not defined by wells that encounter a gas-water contact or test water without gas from a zone below a gas-water contact, as in the blanket-sandstone trend. With increasing depth through

vertically extensive gas-water transition zones, gas saturation in reservoir sandstones decreases and water saturation increases. Eventually gas saturations become sufficiently low that, in terms of cumulative gas production, wells become marginally commercial to noncommercial at a structural position still within the transition zone above the gas-water contact. Therefore, development wells on the flanks of gas accumulations in the tight, Cotton Valley massive-sandstone trend rarely encounter gas-water contacts. If even the smallest amount of gas recovery were commercial, development drilling probably would progress down the full length of transition zones, and gas-water contacts would be encountered in these gas accumulations. The presence of gas-water contacts in gas accumulations within the tight, Cotton Valley massive-sandstone trend suggests that accumulations in this trend, too, are conventional and that a basin-centered gas accumulation does not exist within Cotton Valley sandstones in the northern Gulf of Mexico Basin.

9. A basin-centered, continuous gas accumulation might occur in turbidite sandstones within the Bossier Shale, the lower formation of the Cotton Valley Group. In a currently developing play on the western flank of East Texas Basin, gas production with estimated recoverable reserves exceeding one TCFG is being obtained from sandstone reservoirs, interpreted as slope or lowstand-fan deposits, that are completely encased in marine shales. Reservoirs are significantly overpressured and no water has been encountered in the system. More than 100 successful wells and only one dry hole have been drilled.

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