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# DEPOSITIONAL AND STRUCTURAL CHALLENGES OF THE WILCOX LOBO NATURAL GAS TREND, SOUTH TEXAS

TOPICAL REPORT

(January 1993—October 1994)


Prepared by

H. Scott Hamlin, P. W. Dickerson, Tucker F. Hentz, and S. E. Laubach

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



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16. Abstract (Limit: 200 words)

To increase understanding and utilization of gas resources in the Wilcox Lobo play of South Texas, this report reviews current geological knowledge of the Lobo trend. An additional objective of this report is to identify areas where advancements in geological understanding could lead to substantial improvements in efficient development of the Wilcox Lobo trend natural gas resource. According to published accounts, Lobo sandstones formed in a variety of depositional environments in both shallow and deep marine waters. During and after deposition the Lobo experienced repeated episodes of erosion, faulting, and diagenesis. Thus, accurate prediction of reservoir sandstones' attributes is difficult, and this difficulty is cited by operators as a significant challenge to efficiently targeting the remaining gas resource. Knowledge that would aid emergence of this resource includes information on sandstone correlation and accurate zone identification, depositional systems and facies interpretations, controls on fault pattern variability, and, to a lesser extent, recognition of diagenetic patterns and faults and fractures that are below seismic resolution. Geologic challenges of the Lobo trend are opportunities for targeting increasingly smaller and more difficult-to-detect compartments with advanced technology.

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| Objectives | To increase understanding and utilization of gas resources in the Wilcox Lobo play of South Texas, this report reviews current geological knowledge of the Lobo trend. An additional objective of this report is to identify areas where advancements in geological understanding could lead to substantial improvements in efficient development of the Wilcox Lobo trend natural gas resource. |
| Technical Perspective | This report is based on preliminary regional structural, stratigraphic, diagenetic, and production-pattern studies, a review of published literature, information obtained from Railroad Commission of Texas files, and discussions with Wilcox Lobo operators. The Wilcox Lobo trend of Webb and Zapata Counties in South Texas contains the most prolific tight gas sandstones in the Texas Gulf Coast, yet it is also one of the most geologically complex. To date, published Lobo accounts have only partly answered important questions regarding depositional and structural framework, controls on production, and engineering characteristics of the play. |
| Results | According to published sources and our results, Lobo sandstones formed in a variety of depositional environments in both shallow and deep marine waters. During and after deposition the Lobo experienced massive submarine slumping, repeated episodes of erosion, faulting, and—probably—diagenesis, resulting in a complex stratigraphic and structural framework.<br><br>Consequently, accurate prediction of the occurrence and attributes of reservoir sandstones is difficult. On a regional scale, this uncertainty is cited by operators as the greatest challenge to targeting the remaining gas resource. Key related issues are regional sandstone correlation and accurate zone identification, depositional systems and facies interpretations, and information on fault-pattern variability. Issues that will be increasingly important in the future, when more advanced technologies are applied to this resource, include identification of diagenetic patterns and their controls on rock petrophysical properties and reservoir quality, predictions of intensity and orientation of faults and fractures that are below seismic resolution, and accurate regional and local delineation of flow units and reservoir compartments. |

In the Lobo play, a high degree of reservoir heterogeneity presents an opportunity for targeting increasingly smaller and more difficult-to-detect compartments with advanced technology. Some fault blocks that are currently recognized have areas of less than 80 acres, but smaller and more elusive targets than those now being sought may exist in the play.

**Technical Approach**

Almost no published geologic cross sections and maps are available, and the few that exist are probably not representative of structural and stratigraphic heterogeneity in this unit. According to our preliminary regional stratigraphic correlations and production studies, based on approximately 500 well logs and publicly available production records as well as results of a workshop discussion with Lobo operators, it is clear that projections of production performance and reserves in a highly faulted and sparsely delineated area like the Wilcox Lobo trend contain large uncertainties. A high-resolution geologic framework that can help delineate features such as production fairways would help guide technology deployment.

**Implications**

The importance of resource characterizations in gas sandstone formations has been realized for many years by GRI. Recovery of gas can be enhanced through understanding of the geologic processes affecting the source, distribution, and recovery of gas from these reservoirs. This report provides a current understanding of the Lobo play that will help identify areas where opportunities for more efficient gas production exist through development and application of improved resource characterization technologies.

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## EXECUTIVE SUMMARY

The purpose of this report is to review current geological knowledge of the Wilcox Lobo sandstone natural gas play of Webb and Zapata Counties in South Texas and to identify and describe areas where advancements in geological understanding could lead to improvements in development of the Lobo trend natural gas resource. The Lobo trend is the major low-permeability natural gas producer of the Texas Gulf Coast, having yielded almost 4 Tcf of gas (fig. 1). Lobo production amounted to about 13 percent of domestic tight gas production in 1991. Activity levels are high and increasing, yet the Lobo trend is widely recognized to be among the most complex plays in the Gulf Coast Basin. This is the result of submarine slumping and widespread, intense faulting that greatly hampers sandstone correlation and nearly completely obscures play-wide sandstone patterns. For operators armed with better information, heterogeneous geology has proven to be an opportunity. Our study concludes that the Lobo trend presents further opportunities for using advanced technology to target compartments that are smaller and more difficult to detect, less readily accessed by hydraulic fracturing, and more easily damaged. Effective deployment of advanced technology can be aided by geologic framework studies that put all aspects of a play into context. With the aid of industry experts, key unresolved issues identified in this study include the need for play-wide identification and correlation of reservoir sandstones, definition of depositional systems, systems tracts, and facies, definition of controls on fault architecture—particularly faults that are too small to be resolved with seismic data, and diagenetic and other compositional controls on reservoir petrophysical properties.

## WILCOX LOBO GAS PLAY: GEOLOGIC CHALLENGES AND OPPORTUNITIES

The Wilcox Lobo trend is the major low-permeability natural gas producer of the Texas Gulf Coast (Dutton and others, 1993) having yielded almost 4 Tcf of gas. In recent years Lobo sandstones have accounted for a significant part of domestic tight gas

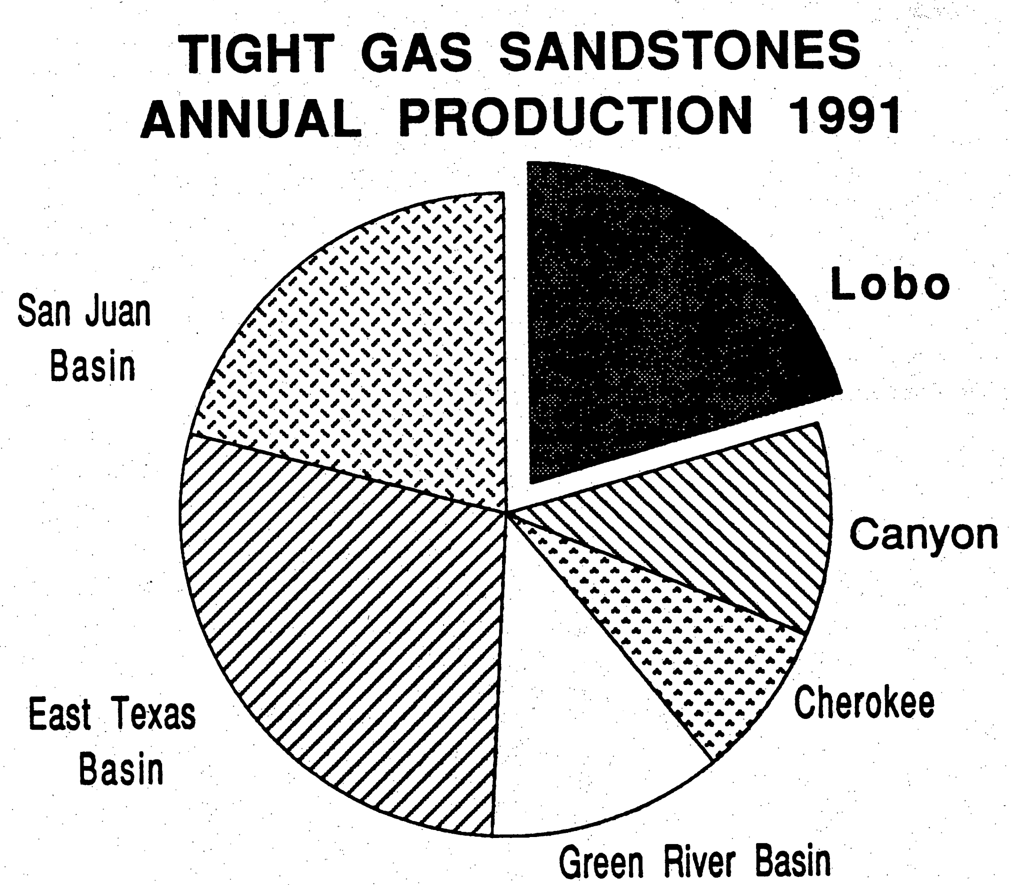



**Figure 1.** Relative productivities of the major low-permeability sandstones in the western U.S. in terms of 1991 annual production.

production: about 13 percent in 1991 (the last year for which a comprehensive tally is available) (fig. 1). Development activities are growing, as marked by rising production rates and an increasing number of producing wells (fig. 2) and active rigs. Yet the Lobo trend is widely recognized among Texas operators as being among the most structurally complex plays in the Gulf Coast Basin, a view substantiated by published accounts of the play and our work. Complex geology has proven to be an opportunity for operators who are armed with better information. The Lobo is challenging and highly rewarding if developed with appropriate methods. In such a setting advanced exploration techniques and completion practices have the greatest potential to offset any decline in gas recovery per well due to a continual movement of activity into lower quality reservoirs over time. The opportunity for successfully targeting smaller, higher risk reservoir partly accounts for the widespread use of 3-D seismic in the Lobo play (Improved Recovery Week, 1994) and points to future potential for technology applications to access this emerging gas resource.

Framework studies that put all aspects of a play into context are useful guides to the deployment and effective use of advanced technology. Such studies can also point to areas where new technology is needed. With the ultimate objective of helping to increase understanding and utilization of gas resources in the Wilcox Lobo play of South Texas, this report reviews current geological knowledge of the Lobo trend. Another key objective of this study was to identify areas where advancements in geological understanding could lead to substantial improvements in efficient development of the Wilcox Lobo trend natural gas resource. The stratigraphic and structural complexities that currently challenge Lobo operators represent an opportunity for increasing success rates through improved understanding of controls on productivity. An inadequate knowledge of key reservoir attributes, such as petrophysical properties, compartment size, and fluid flow patterns, results in inefficient and incomplete exploitation of the gas resource. The importance of knowing these attributes will only increase as more technologically sophisticated approaches are used in the play.

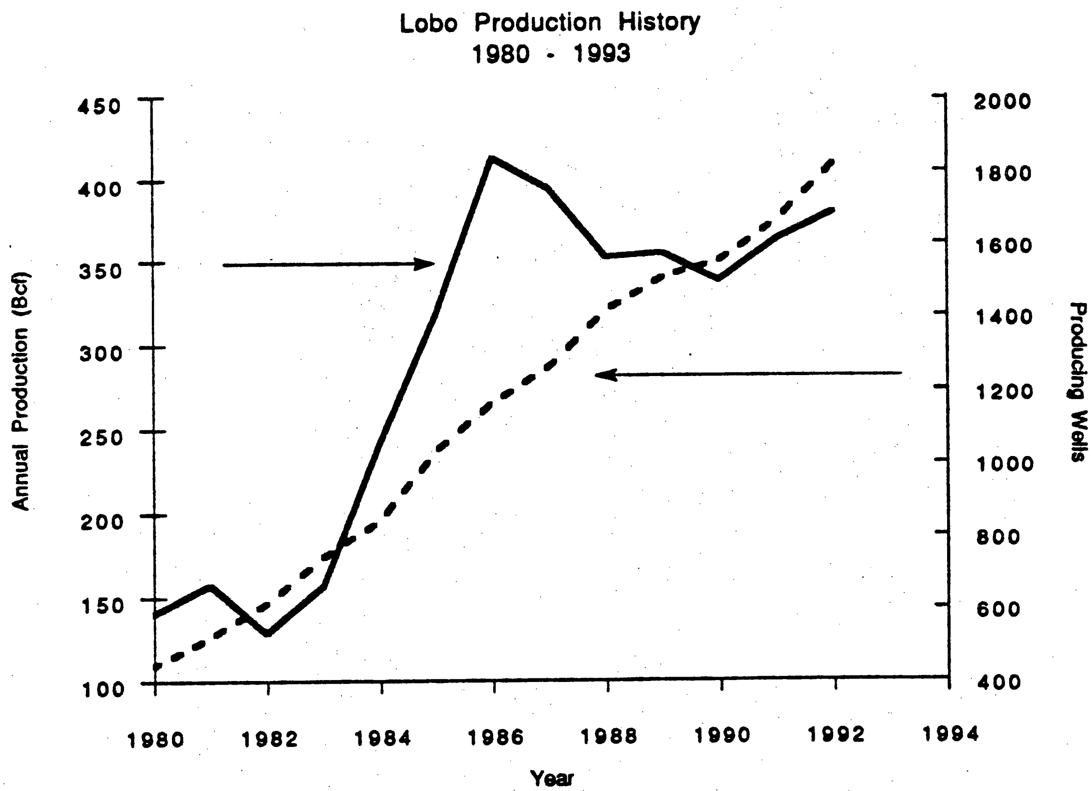



Figure 2. Annual productions and numbers of producing wells for the Lobo play, 1980 to 1993.

## Key Issues

This report is organized on the basis of unresolved stratigraphic, diagenetic, and structural issues or challenges that we identified as opportunities for more efficient gas production through improved resource characterization (table 1). The most fundamental problem Lobo operators face is geologic heterogeneity leading to uncertainty in the location, size, and quality of reservoir rocks. With current technology, this can potentially lead to nonoptimal well placement, inappropriate completion design, or inadequate reservoir modeling. In the future, wherever smaller and more inconspicuous reservoir compartments must be found, uncertainty about overall arrangement of sandstone fairways and faults will increase risk of using expensive technology in nonprospective areas. This uncertainty could make certain parts of the resource uneconomic. New technologies should be focused in areas where reliable framework studies have identified where attractive targets are most likely to be found.

The main causes of geologic complexity in Wilcox Lobo reservoirs are:

- Depositionally controlled variations in net pay distribution and erosional truncation of reservoir compartments,
- Diagenetic overprint of reservoir facies,
- Intense faulting and fracturing.

The research issues listed in table 1 are all related to these causes of variability. Lobo operators, through telephone interviews and meetings, played a key role in helping us define the issues listed in table 1 and to rank their near-term importance to Lobo development. At a Gas Research Institute-sponsored workshop in Houston in September 1994, representatives of 12 Lobo operating companies—which together account for the majority of Lobo production—and one service company, reviewed the issues in table 6 and the areas of geologic investigation that have the greatest potential to provide the information and technology necessary to overcome these challenges.

Table 1. Challenges, approaches, and technical benefits.

| Challenge | Approach | Technical Benefit |
|---|---|---|
| Create regional structural maps, understand controls on sandstone and fault trends | Physical and numerical modeling, remote sensing, gravity, and magnetic studies, tie log correlations to seismic data | Reveal structural controls on sandstone deposition and fault patterns, provide context for reservoir compartment studies; improve interpretation of 3-D seismic |
| Correlate sandstones and identify producing zones with a high degree of certainty play wide | Compile log data base from wells having minimal deformation and local type logs, correlate flooding surfaces and unconformities, biostratigraphic and lithostratigraphic signatures | Improve structural and stratigraphic mapping, reserve allocation, play-wide comparisons to establish controls on productivity |
| Define depositional systems and map facies | Integrate sandstone architecture, core descriptions, and biostratigraphy | Predict prestructure prediagenesis sandstone configuration and reservoir trends and project trends into undrilled areas; predict reservoir properties |
| Discover diagenetic controls on petrophysical properties; develop predictions of reservoir quality | Compare sandstone composition and diagenesis to depositional setting, structural history and setting with respect to faults, and basin hydrodynamics | Predict areas of enhanced porosity and permeability, identify regions sensitive to damage, calibrate log analysis; identify targets for advanced drilling |
| Quantify fault and fracture patterns that are below seismic resolution; quantify their impact on current and future development practices | Identify fractures and faults in core and on logs; develop predictive models; use advanced core analysis methods to map fractures | Predict flow conduits, barriers within sandstone due to features below seismic resolution; identify targets for advanced targeting; document permeability anisotropy |
| Define reservoir compartments, flow units, and other key parameters regionally using pressure, water, gas chemistry, and stress direction information | Pressure and geochemical mapping techniques within the stratigraphic, structural, and petrophysical contexts | Document fault seal properties, fluid migration directions, and fluid compositions for log analysis; anticipate drilling problems |

## Report Structure

Following a general overview of attributes of the Wilcox Lobo play, this report describes the geologic framework issues and their significance, identifies and describes the current published information on the topic, and describes the technical approaches needed to address future development challenges.

# OVERVIEW OF WILCOX LOBO TREND

## Geologic Setting

The Paleocene Wilcox Lobo trend comprises a series of variably geopressured, generally low permeability sandstones in one of the most highly faulted and stratigraphically ill defined geological settings in the Gulf Coast region (O'Brien and Freeman, 1979). The Lobo interval forms part of the larger downdip Wilcox trend, a region characterized by thick shales and thin sandstones, high fluid pressures, and closely spaced faults (fig. 3). Total thickness of the downdip Wilcox ranges from 5,000 to 12,000 ft. The Lobo interval, which is located in Webb and Zapata Counties and includes only the lowermost part of the Wilcox Group, is generally less than 1,200 ft thick, although thicker Lobo intervals are preserved locally near the Rio Grande. Thickness and extent of equivalent intervals in Mexico have not been described. Lobo sandstone reservoirs individually are generally less than 100 to 200 ft thick and are interbedded with thicker shales (fig. 4). The Lobo is separated from overlying Wilcox sandstones by 500 to 1,200 ft of shale and is underlain by an equally thick shale in the Midway Group. Depths to Lobo reservoirs vary widely between 5,000 and 14,000 ft.

Numerous studies of the Wilcox Group have been published, but only a few of these deal specifically with the Lobo. Regional Wilcox descriptions (Fisher and McGowen, 1967; Edwards, 1981; Bebout and others, 1982; Loucks and others, 1986) provide the general structural, stratigraphic, and diagenetic context necessary for field- and reservoir-scale interpretations. Published studies of the Lobo trend (O'Brien, 1975; Claughton, 1977;

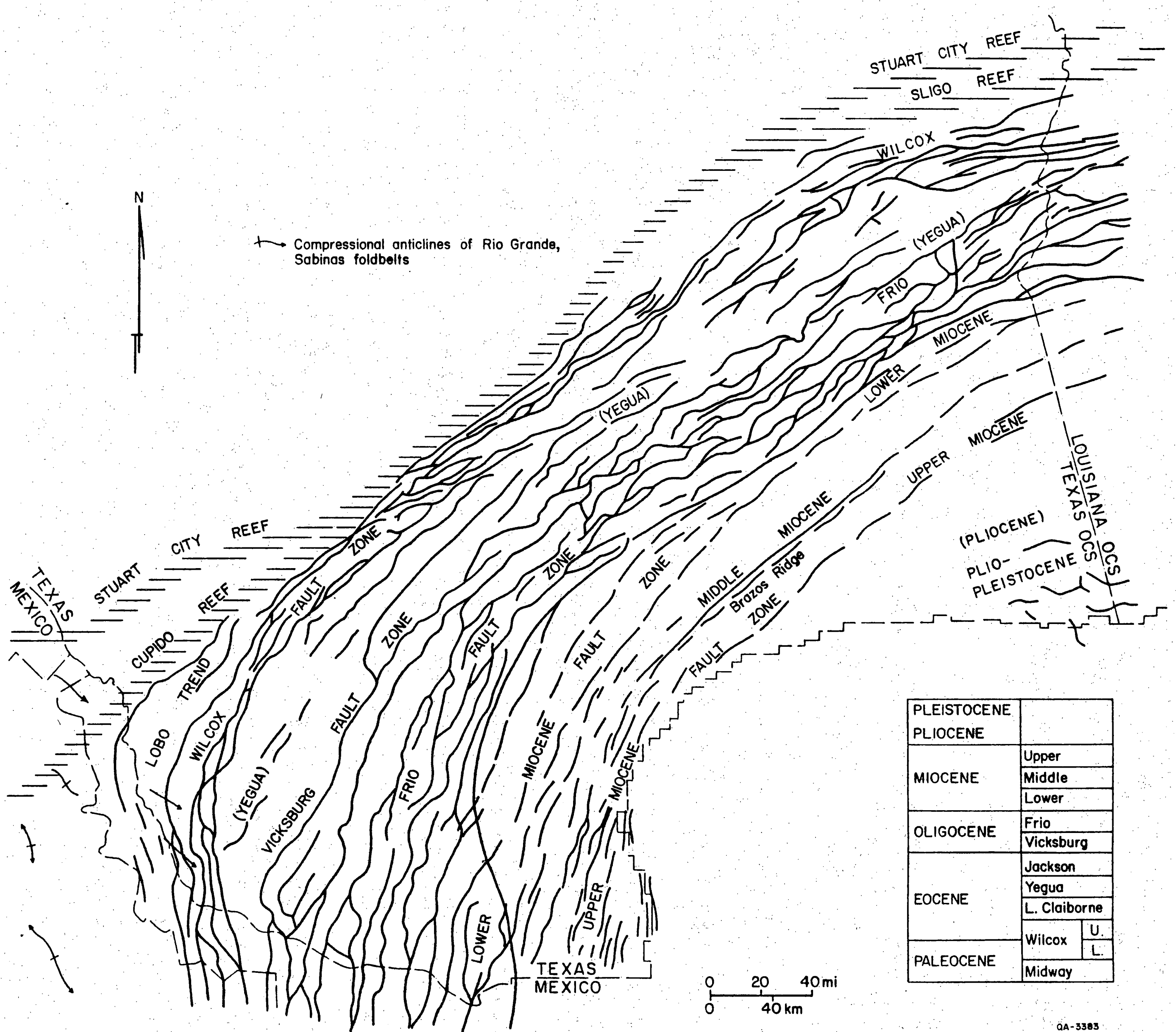



**Figure 3.** Regional fault zones and producing trends for the Texas Gulf Coast Tertiary Basin. From Ewing (1986).

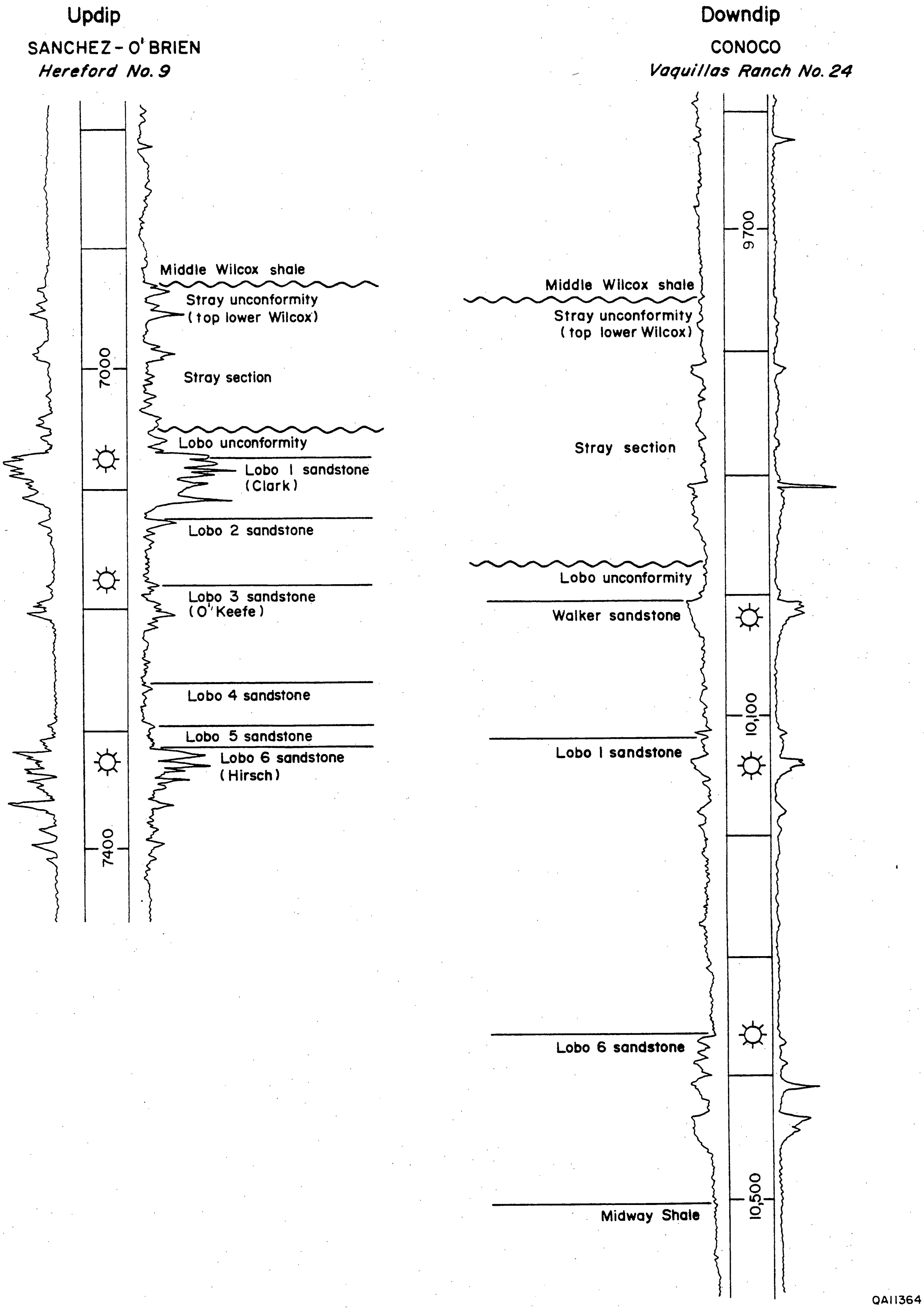



**Figure 4.** Typical logs from the lower Wilcox Lobo trend showing productive sandstones and unconformities. Modified from Long (1986). Wells locations shown in figure 11.

O'Brien and Freeman, 1979; Henke, 1982; Alexander and others, 1985; Long, 1986; Robinson and others, 1986; Berlingen and others, 1988) provide good basic geologic and engineering information, but much remains to be learned about enigmatic Lobo reservoirs. Depositional setting and structural history are still poorly understood. The most useful information for our study came from the unpublished data and experiences of the Lobo operators themselves.

## Engineering Characteristics

Petrophysical data for Lobo reservoirs were derived from published reports, unpublished data from operators, and the files of the Railroad Commission of Texas. Porosities in productive Lobo sandstones range from 12 percent in the downdip part of the trend to the east to as much as 25 percent in the western, updip portion of the trend (Robinson and others, 1986) (table 2). Lobo sandstone permeabilities can vary widely on a well-by-well basis; Robinson and others (1986) reported in situ gas permeabilities ranging from 0.0003 to 0.5 md. A median permeability to gas of 0.0327 md is reported in Railroad Commission (1980, 1981, 1982) files, but other operators describe permeabilities reaching several tens of millidarcys in a few zones. Permeability patterns in the Lobo do not fit a simple pattern and are not readily predictable from current knowledge.

Reservoir-quality rock is typically 10 to 60 ft thick, and locally, net pay thicknesses as high as 150 ft have been reported. Porosity cutoff is 10 to 12 percent for net pay determination and is high because of the abundance of clay in the Lobo sandstones. Water saturation ranges from 25 to 70 percent (table 2). Because shaliness increases water saturation, higher water saturation values are not necessarily indicative of water production. Capillary pressure measurements should be run in poor-quality rock if there is a question of potential water production.

As the Lobo thickens toward the coast, reservoir temperatures increase from 175°F updip (at about 6,000 ft) to 310°F downdip (at about 12,000 ft). Average temperature gradient is approximately 2°F/100 ft. The Lobo sandstones are overpressured, and pressures range

Table 2. Wilcox Lobo production data and engineering parameters.

| | |
|---|---|
| Estimated resource base: | 8 Tcf |
| Number producing completions in 1992: | 1732 |
| Cumulative production through 1992: | 3.995 Tcf |
| Annual production in 1992: | 395 Bcf |
| Net pay thickness: | 10 to 160 ft |
| Porosity: | 12 to 25% |
| Permeability (in situ gas): | 0.0003 to 30.0 md |
| Water saturation: | 25 to 70% |
| Reservoir temperature: | 175° to 310°F |
| Reservoir pressure: | 3,000 to 8,000 psi |
| Typical hydraulic fracture stimulation: | 100,000 gal gel/200,000 lb proppant |
| Prestimulation production rate: | 100 to 1,500 Mcf/d |
| Poststimulation production rate: | 300 to 50,000 Mcf/d |
| Average recovery per well: | 3.2 Bcf |

from 3,000 psi at 6,000 ft to 8,000 psi at 11,000 ft (Robinson and others, 1986). Average pressure gradient is approximately 0.6 psi/ft. Regional maps of pressure and temperature patterns do not exist. High pressures and temperatures can create severe problems for drilling, logging, and completion.

Perforations are usually made on a one-shot-per-foot density across the zone of interest. The gross thickness of Lobo perforated intervals ranges from about 10 to 300 ft. Fracture stimulation treatments on 29 wells in 1981 averaged 101,800 gal of gel and 207,000 lb of proppant, but prior to 1981 fracture treatments were larger, averaging 395,000 lb of proppant in 1980. Smaller fracture treatments and more technologically advanced fracture designs reflect an effort to optimize fracture length. Because sand crushing and embedment can be a problem in the Lobo sandstone, higher strength proppants are commonly used. There are no published stress profiles for the Lobo trend. Marine mudstones—potential fracture height-growth barriers—have not been systematically mapped across the trends, and petrophysical properties of these rocks have not been described. Acid is not recommended because of potential formation damage caused by the reaction with iron-rich chlorite pore-lining clay (Dutton and others, 1993). However, as will be described, some chlorite in the trend is not iron bearing, and may not be particularly susceptible to damage.

## Production Trends

By the end of 1992, the Wilcox Lobo had produced 3.995 Tcf of gas from 318 reservoirs in 158 fields, qualifying the Lobo as a major unconventional gas resource (Dutton and others, 1993). Lobo cumulative production is almost twice the gas volume of early estimates of ultimate recoverable reserves (O'Brien and Freeman, 1979), making the Lobo an excellent example of reserve growth through geologic targeting. Opportunities still abound for locating overlooked or unrecognized geologic targets using conventional and currently available advanced resource development technologies. Under these circumstances we suspect that ultimate production will be at least twice the current cumulative figure (table 2). However, in view of the extensive geologic heterogeneity of the Lobo, substantially greater reserve growth is a possibility if advanced approaches can be effectively directed to parts of the play where such targets can be economically exploited.

Because historical discovery and production trends can be used to project future potential, Lobo production statistics are reviewed here. Additionally, historical production data can reveal the amount and nature of variability that exists among Lobo reservoirs and wells. Production data were derived from the files of the Railroad Commission of Texas.

Development of the Lobo play began in the early 1970's and reached a peak in 1986, when annual production exceeded 400 Bcf from 1,200 wells (fig. 2). In recent years, however, drilling activity and production have been increasing again (fig. 2): in 1992, 395 Bcf was produced from 1,732 wells. The number of new reservoir discoveries has declined from the highs of the middle 1980's, but this trend also appears to be reversing (fig. 5). Individual Lobo reservoirs display a variety of production trends, some steeply rising and others in decline (fig. 6). These data suggest that, although the Lobo is a relatively mature play and most of the "easy" discoveries have already been made, Lobo operators remain active and optimistic, willing to face increasing technological challenges to continued successful play development.

Historical production data reveal large variabilities in reservoir and well productivity. A few reservoirs have produced more than 100 Bcf, but the median reservoir cumulative production is 2.1 Bcf (table 3). Some of this variability is a result of inconsistent reservoir definitions made by the Railroad Commission of Texas (RRC), but most is real: each RRC-designated Lobo reservoir usually represents one Lobo zone in one field. Approximately one-third of all Lobo reservoirs have produced less than 1 Bcf, whereas 2 percent of Lobo reservoirs account for approximately one-third of production (fig. 7). In the middle of the range, however, two-thirds of the reservoirs account for two-

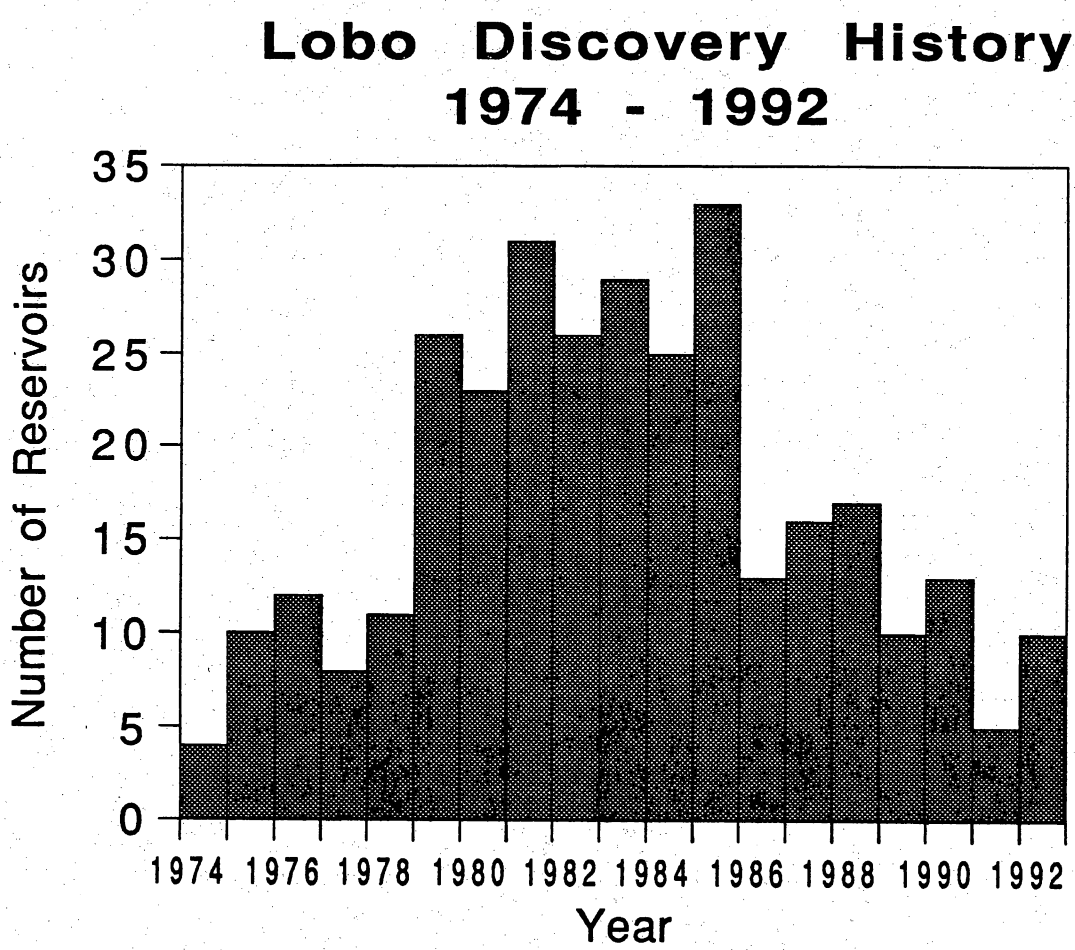



Figure 5. Number of new Lobo reservoirs discovered each year from 1974 to 1992.

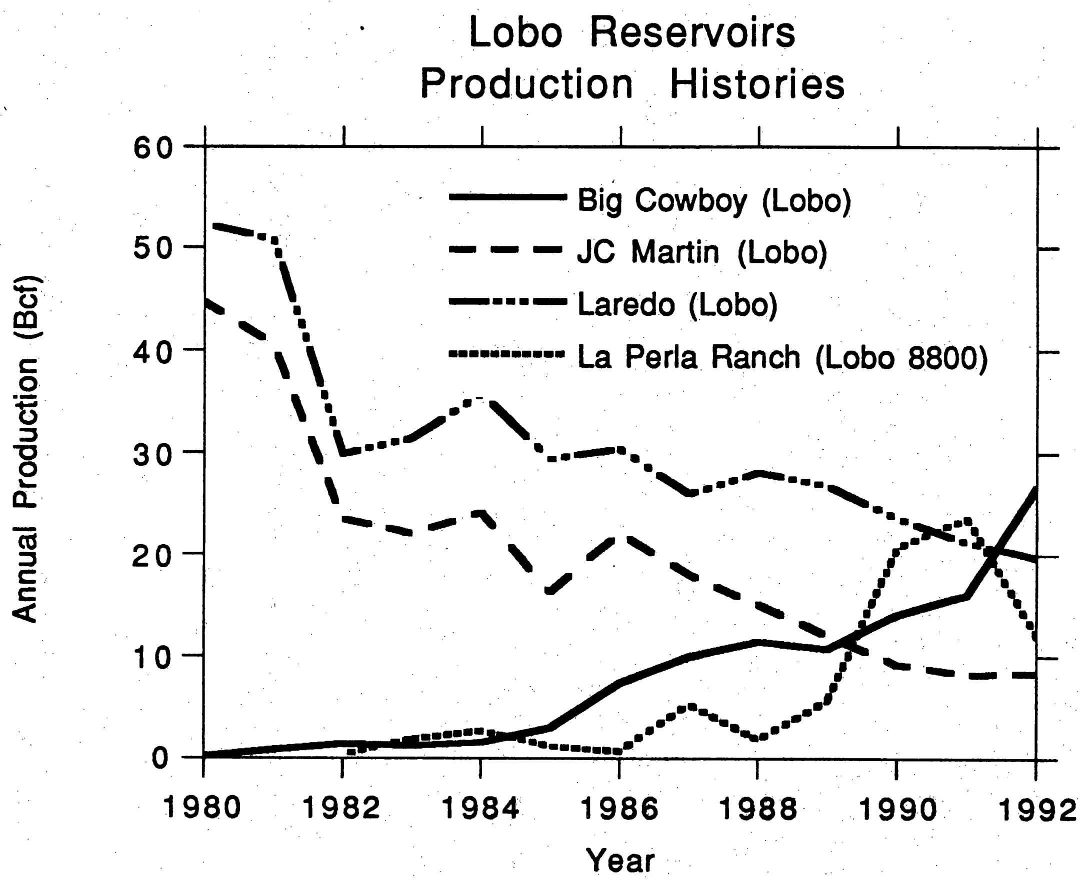



Figure 6. Production histories for selected Lobo reservoirs.

Table 3. Wilcox Lobo cumulative production statistics through 1992 (Bcf).

| | **Wells (n = 150)** | **Reservoirs (n = 318)** |
|---|---|---|
| Minimum | 0.013 | 0.003 |
| Maximum | 11.0 | 578.1 |
| Mean | 1.6 | 12.6 |
| Median | 1.0 | 2.1 |
| Standard deviation | 1.8 | 44.3 |

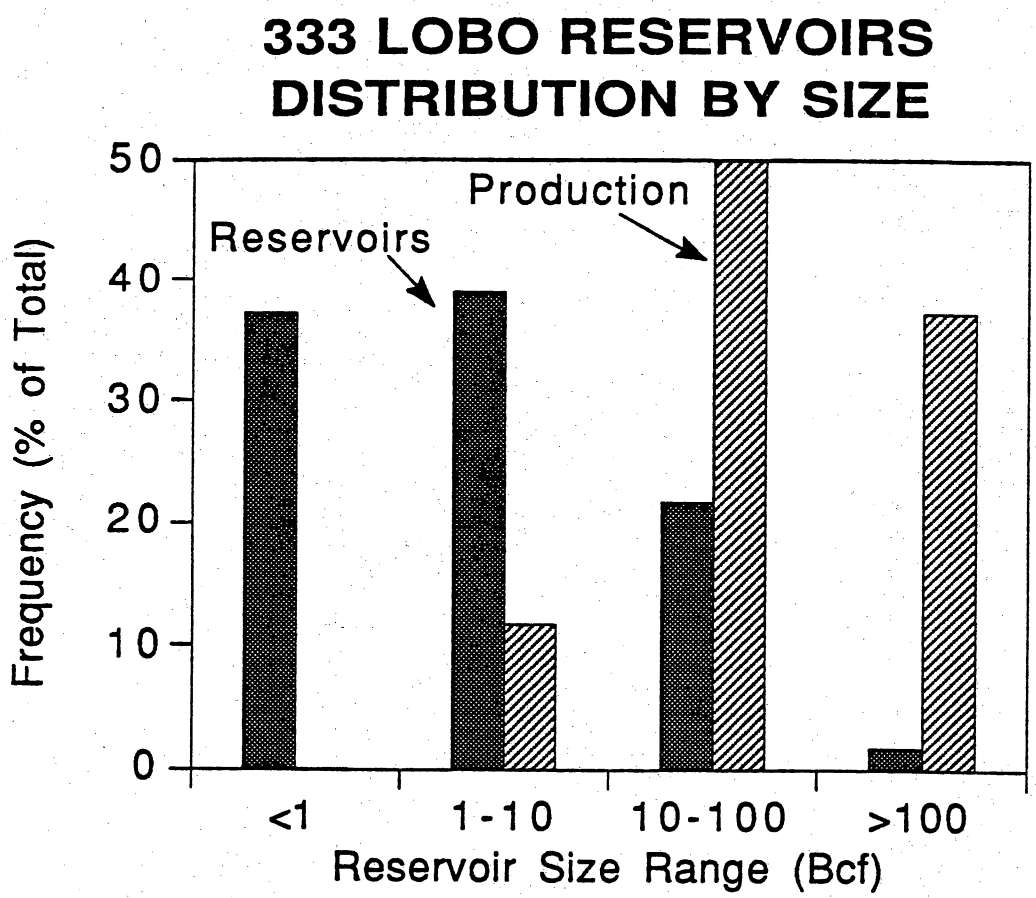



**Figure 7.** Distribution of Lobo reservoir size classes in terms of total Lobo gas production and reservoir frequency.

thirds of the production. Reservoirs in this large group range in size from 1 to 100 Bcf and form the main target for exploration and development.

A group of 150 Lobo wells was selected as a representative sample for analysis of individual well productivity. The median cumulative production of this group is 1 Bcf, but per-well production reaches 10 Bcf in a few wells (table 3). Daily production rates also vary widely between about 100 and 50,000 Mcf/day. Finally, Lobo wells display differing production decline trends (fig. 8) and porosities (fig. 9). Variabilities in well productivities reflect heterogeneities in reservoir compartment sizes and petrophysical properties.

## DEVELOPMENT CHALLENGES

The discussion that follows focuses on issues listed in table 1. At a discussion workshop, geologists and engineers active in the Lobo trend rated a regional perspective on sandstone identification and targeting of Lobo producing zones as a very important near-term need that would not be met by industry efforts. Tectonic controls on deposition and faulting were considered to be an important related issue. Diagenetic controls on rock properties, compartment internal structural geometry (as a separate issue from fault trap identification using 2-D and 3-D seismic, which is part of current practice), and fluid pressure, fluid flow, and stress patterns were indicated to be key issues that are now not having a direct impact on development plans, but that will be important as the play evolves.

### Tectonic Controls on Deposition and Faulting

An understanding of sandstone correlation, zone identification, depositional systems, and facies patterns, as well as insight into fault patterns and styles, is most comprehensible in the framework of a well-constrained regional structural (tectonic) framework. Although the Gulf Coast Basin has a well-understood structural framework, that section of the basin that contains the Lobo trend has several special characteristics that have only recently been appreciated. These relate to the governing possible roles of

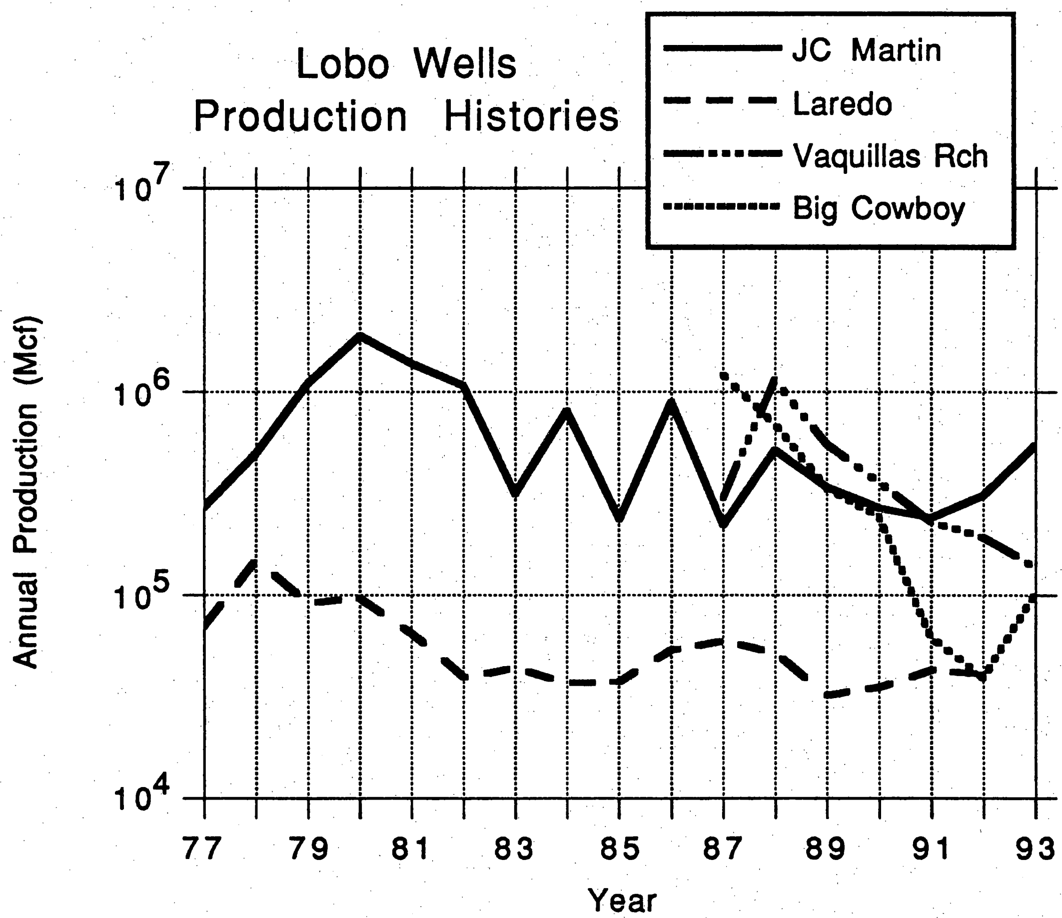



**Figure 8. Production histories for selected Lobo wells.**

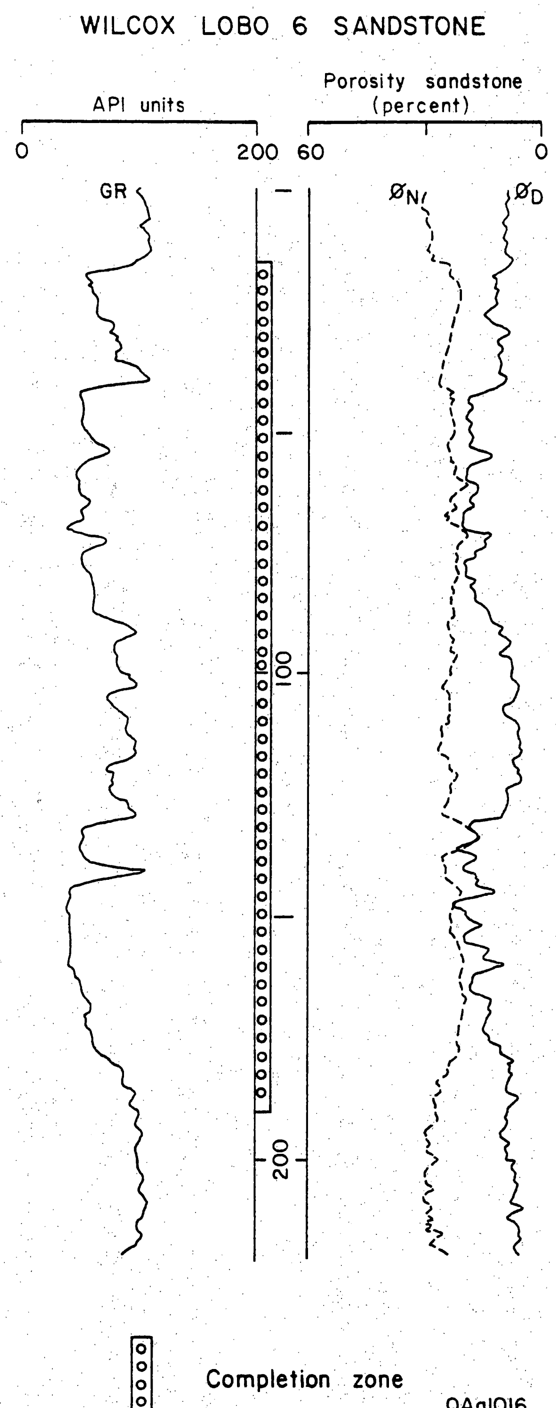



**Figure 9.** Porosity logs from a typical Wilcox Lobo well showing the Lobo 6 sandstone completion zone. From Berlinger and others (1988). Well identification and actual zone depth are not reported.

interrelated Laramide tectonism and salt tectonics governing the kinematic evolution of the region. The possible effects of these events on the evolution of the Lobo are intriguing but currently ill defined. Yet even within the established Gulf Coast Basin history, the depositional setting and structural history of the Lobo trend are poorly understood (Long, 1986). In this section of the report, the setting of the Lobo trend is briefly reviewed and some ways that structural controls can be used to constrain sandstone deposition and fault patterns are described.

The Gulf Coast Basin originated with rifting during the Triassic–Jurassic as North America began separating from Africa–South America (Buffler and Sawyer, 1985). Along the Gulf Coast, slow rates of sediment influx persisted throughout the Mesozoic until regional uplift and tectonism in western North America provided a surge of terrigenous clastic sediment during the Cenozoic (Galloway, 1989). Texas Gulf Coast Tertiary formations include a series of sandstone-rich wedges composed of coastal-plain and marginal-marine deposits separated by transgressive marine shales. These formations, which thicken and dip basinward, are segmented by regional strike-parallel normal fault zones (fig. 3). Low-permeability gas reservoirs occur along the deeply buried, downdip margins of Texas Gulf Coast Tertiary formations, where fine-grained sandstones are thinly interbedded with shales. Because of basinward dips, gas-productive trends of successively younger formations are found progressively farther to the southeast.

In this setting, the Lobo trend developed as a highly heterogeneous detached slump mass (Long, 1986) having extensive soft-sediment deformation features, syn- and post-slumping faults—possibly of several ages—and polyphase development of erosion surfaces (fig. 10). Source areas have not been identified and depositional patterns governing original sandstone shape are almost completely obscured by this deformation. The role of basement structure in controlling geometry and internal structure of the slump mass is unknown, but it might provide useful insight into the orientation and crosscutting relations among reservoir-scale faults.

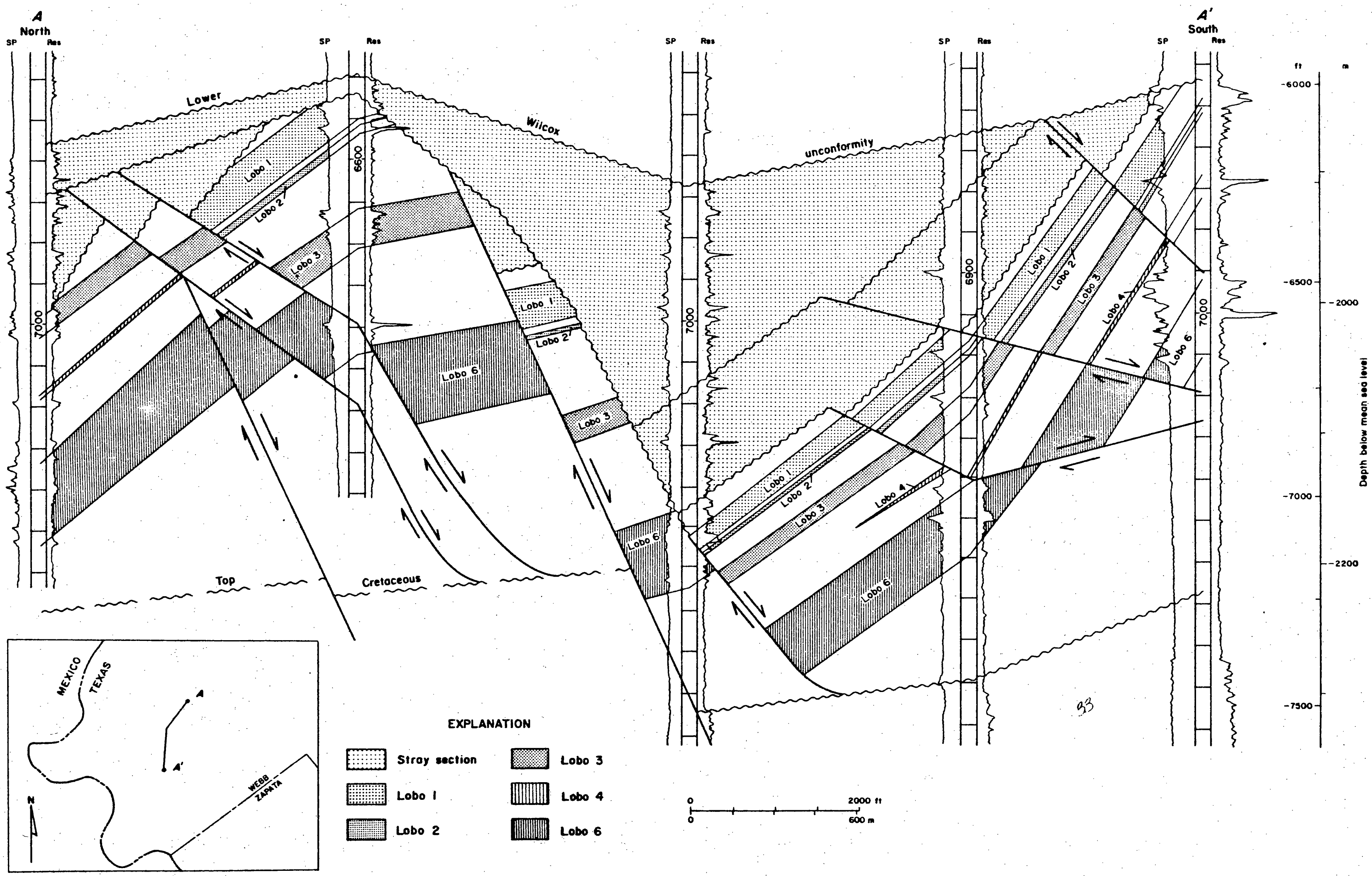



Figure 10. North-south cross section of Laredo (Lobo) field, Webb County, Texas, showing complex configuration of faults and unconformities that compartmentalize Lobo reservoirs. From Railroad Commission of Texas (1977).

Among unresolved issues relevant to Lobo production that pertain to regional tectonics are the following:

- Can source areas (that control sandstone composition and hence reservoir quality) and sandstone depositional patterns (pre-faulting sandstone trends) be identified or predicted from regional models?
- Does deep (sub-Midway) structure exert significant controls on fault patterns within the Lobo or location of productive fairways within the Lobo? It is possible that basement structures localize faults and folds higher in the section above the Midway; if so, can this information be used to help extrapolate structural information from areas of dense Lobo well and seismic control to areas having less dense coverage? Is there a consistent structural pattern associated with prolific production fairways? Can remote sensing and potential fields (gravity, magnetic) mapping be used to identify these areas?
- Is late-stage Laramide salt mobilization responsible for some of the deformation of the Lobo interval? Has late salt movement enhanced or breached Lobo traps? What—if any—relationship is there between salt tectonics and areas of reverse faults and repeated section? Can salt tectonics modeling enhance interpretation of complex Lobo structural traps; in particular, can it guide 3-D seismic interpretation?

Laramide and pre-Laramide compressional tectonism is manifested as predominantly northwest-trending folds and thrust faults in northeastern Mexico, along the western margin of the Texas Gulf Coast Basin, and also possibly as some of the large basement uplifts, such as the San Marcos Arch, that occur within the Gulf Coast Basin (e.g., Laubach and Jackson, 1990). The configuration and possibly the evolution of the structural trough between the San Marcos Arch and Laramide structures in Mexico and along the Mexico–Texas border are reflected in shifts in strike of some of the large faults in the Lobo trend. Although a relationship has not been documented in the literature, the kinematic evolution of tectonic framework elements such as the San Marcos Arch and the Laramide deformation belt may also have played a role in governing sandstone depositional patterns, source areas, and erosional history of the Lobo trend.

The timing and style of Lobo deformation suggest to us that salt mobilization—possibly initiated by Laramide compressional deformation—may also have affected structural development of the Lobo trend. Preliminary examination of salt structures within and near the Lobo trend and comparison of the Lobo slide with Neogene analogs in the Gulf Coast Basin (Morton, 1993) suggest that salt tectonics could have played a significant role in Lobo slump and fault development. Some of this movement postdates Lobo deposition, as shown by salt domes at Pescadito (mid-Eocene, Yegua), Moca (late Eocene, Jackson Group), and elsewhere.

Recognition of the role of salt mobilization in Lobo evolution raises the possibility that sophisticated salt tectonics models, which have had marked success in unraveling difficult structural problems in the deep-water Gulf of Mexico, could be applied to the Lobo. Our preliminary physical modeling of Lobo structures suggests that this approach can shed light on the kinematic evolution of Lobo structure and interpretation of cryptic fault patterns. Such insights can aid interpretation of 3-D seismic information.

A challenge to regional structural analysis of the Lobo is delineation of fault trends. Although conventional well-log-based mapping and 2-D and 3-D seismic data are critical to such efforts, the recognition of possible basement and salt tectonic control on fault patterns suggests that physical modeling studies could be useful for guiding interpretation and correlation of such information.

Another approach to this problem is to use indirect methods to document fault patterns where dense subsurface information and seismic data are sparse. Applicable methods include remote imaging studies and potential fields data (gravity and magnetic maps). Elements of such a study would include interpretation of satellite and Shuttle images and correlation with seismically defined features. Interpretation of gravity and magnetic data should also be undertaken, leading to inferences of the geometry and structural relief of major basement structures. A comparison should be made—at basement level, within the Lobo interval, and at the surface—of structural features. Resulting maps would then be compared with production patterns.

On the basis of our initial inspection of Shuttle photographs and Landsat and Thematic Mapper images, we conclude that these high-altitude pictures reveal surface and subsurface structures in Mexico and South Texas that affect the Lobo producing interval. Trends of large features such as broad, northwest-trending basement salients and broad folds are visible, and these features are evident in Lobo producing intervals on several published maps and maps on file with the Railroad Commission. Public-domain gravity and magnetic data indicate that the same dominant grains exist for basement structure. High-altitude images also reveal cross faults and joints having northeast strikes. Published maps and reports on file with the Railroad Commission show that both of these grains are evident in the Lobo producing interval.

These observations suggest that high-resolution imagery, in conjunction with potential field data (gravity, magnetic maps), could be used to supplement structural maps constructed from geophysical well log data and 2-D seismic data to extrapolate major fault, fold, and fracture trends between areas of dense well control and/or 3-D seismic coverage. Integrated imagery and potential fields data could help identify structural domains that may be associated with production trends, to predict type and orientation of faults and folds in areas of sparse data. Effects of Laramide and later deformation could be reconciled, leading to a unified structural/tectonic history that could help clarify structural, pressure, and production patterns.

The effectiveness of a remote sensing study in contributing to understanding of subsurface structure depends on the care taken to interpret features on images in relation to specific geological features. In well-exposed terrain, the geological significance of lineaments or other physiographic features can be observed directly. In areas where structures of interest are buried, there will only be an indirect relationship, or none at all, between buried structure and surface topography. Where cover is present—as in South Texas—topographic data can still provide valuable subsurface structural information, provided that structures, such as faults and folds, are imprinted in the cover. Mechanisms such as differential compaction and image interpretation should be thoroughly integrated with available geological and geophysical data. Figure 11 is an example of imagery in the area of the Lobo play with some of the visible structural features indicated.

## Sandstone Identification and Targeting

The Wilcox Lobo interval includes seven distinctive sandstone zones, generally termed Lobo 1 through Lobo 6 and Walker, overlain by an irregularly interbedded sandstone/shale section called "stray" (fig. 4). Several of the Lobo zones extend throughout the play, whereas others are more localized (fig. 12).

Although Lobo zones are laterally continuous, they are composed internally of discontinuous sandstone lenses interbedded with thin shales. Regional patterns of such lenticular sandstones is a key unknown in the Lobo play. Some are lobate, whereas others are channel shaped. Lobe patterns and channel trends are unknown. Lobo sandstones typically have gradational bases and sharp tops and display an upward increase in bed thickness and grain size. The lowermost zone, Lobo 6, is the most extensive and generally the thickest ($\leq$ 300 ft thick). Lobo 5 through Lobo 2 zones are generally each less than 50 ft thick and are less extensive than Lobo 6, whereas Lobo 1 is similar to Lobo 6 in distribution and thickness. The Walker zone overlies Lobo 1 and occurs mainly in Webb County. The Walker zone is typically composed of a single, 50-ft-thick sandstone. The major Lobo sandstones are typically separated from each other by shales of equal or greater thickness (fig. 4). The stray section overlies the Lobo sandstone zones, is bounded by unconformities, and ranges from about 200 to more than 1,000 ft thick. Although dominated by sandy and

Figure 11. Shuttle photograph of part of the Lobo trend showing broad fold and features interpreted to be fault traces.

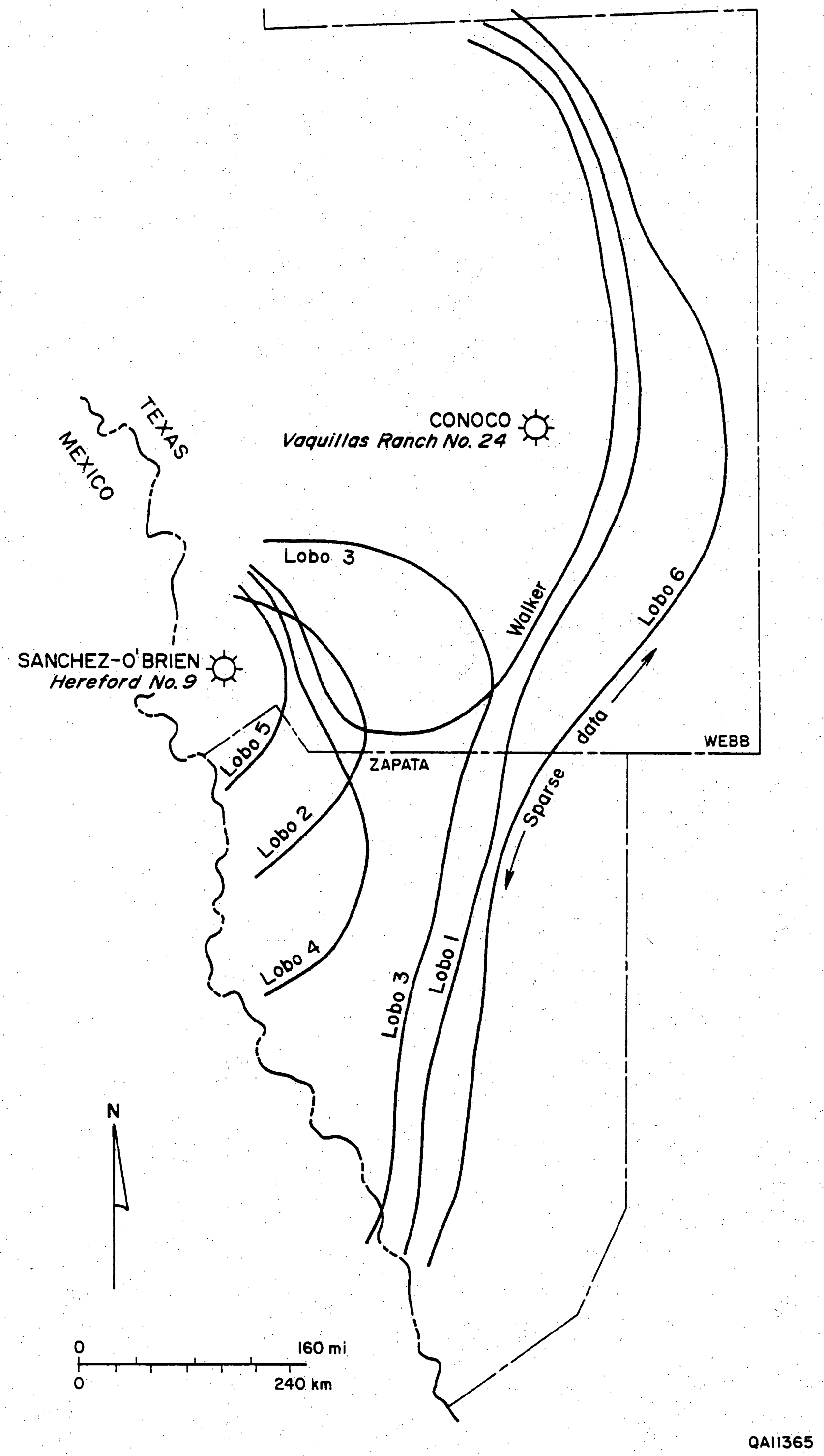



Figure 12. Lateral extents of Lobo productive sandstones, also showing locations of typical logs (fig. 4). Modified from Long (1986).

silty shales, the stray section contains productive sandstone locally. Most Lobo production, however, comes from the Lobo 6, Lobo 3, Lobo 1, and Walker zones.

Extensive postdepositional deformation and erosion profoundly modified Lobo stratigraphy (fig. 10). Shortly after deposition, the main Lobo zones were subjected first to intense faulting and then to erosional truncation to form the Lobo unconformity. The stray section was then deposited upon the Lobo unconformity and subsequently was subjected to a second phase of faulting and erosion. Additional phases of deformation and/or erosion occurred in some areas. The Lobo unconformity commonly truncates the shallower zones (Walker, Lobo 1 through Lobo 3) and more rarely cuts as deep as Lobo 6, imparting lateral discontinuity to sandstones that were deposited as laterally continuous sheets. Closely spaced extensional faults also truncate Lobo sandstones and result in "missing sections." Because the shapes and distributions of Lobo reservoirs depend not only on depositional facies but also on postdepositional faulting and erosion, the interrelationship of the effective stratigraphic and structural processes must be understood in order to develop predictive tools for locating areas of optimal reservoir development. Patterns of sandstone geometry and erosion surfaces could contain information that would help to identify production fairways. Determining pre-faulting sandstone shape could be important in design of hydraulic fracturing and directional drilling strategies.

Several depositional environments have been proposed for the Wilcox Lobo within the broad context of an outer-shelf to upper-slope paleoceanographic setting. Deltas, barrier/strandplains, offshore bars, and turbidites are the possibilities cited by previous workers (O'Brien and Freeman, 1979; Henke, 1982; Alexander and others, 1985; Long, 1986). The outer-shelf/upper-slope setting was established by biostratigraphic analyses reported by Lobo operators and confirmed by similar analysis performed during our study. Previous environmental interpretations are based primarily on core descriptions. Although vertical sequences of lithologies and sedimentary structures form a key component of environmental reconstruction, specific sequences are not unique to particular environments and therefore must be interpreted within the context of the depositional architecture—that is, the three-dimensional geometries and internal stratal patterns of the sandstones.

Positive zone identification and play-wide zone correlations must be established before useful sandstone maps can be constructed for determining depositional architectures. Because the complicated structural setting makes stratigraphic correlation difficult, play-wide sandstone mapping has not been attempted in previous studies. The most appropriate approach to such a study would build on the subregional correlations that have been established by operators by expanding and integrating them into a play-wide framework. Detailed sandstone maps, interpreted in conjunction with core descriptions, biostratigraphy, and borehole-imaging logs, should be used to build a depositional facies model for each Lobo zone. The facies models can then be used to reconstruct sediment transport directions and the distributions, orientations, and dimensions of each reservoir sandstone. Facies models also have important implications concerning original (pre-diagenesis, pre-deformation) reservoir petrophysical properties. Thus, Lobo facies models can become powerful tools for projecting trends into undrilled areas and for targeting specific zones in optimal locations.

Depositional processes form only one component of geologic controls on reservoir properties; the postdepositional processes of deformation and diagenesis have profoundly modified Lobo reservoirs. Reconstructing depositional environments, however, is the critical first step in documenting geologic controls on productivity. Lobo deposition is closely associated with gravitational deformation—slumping, sliding, and down-dip normal faulting—and, we suspect from published maps that postdepositional biaxial stretching (possibly related to differential movement of the slump mass over basement structure) is manifested in arrays of normal faults having varying intersection angles. Reconstruction of depositional environments, then, must be integrated with analysis of structural processes in order to determine how the interrelationship between stratigraphy and structure affected ultimate reservoir characteristics. Diagenetic analysis of compaction and cementation must also proceed within an established stratigraphic and structural framework. Using this comprehensive approach, specific controls (depositional, structural, or diagenetic) on specific reservoir attributes can be determined.

## Diagenetic Controls on Rock Properties

Wilcox Lobo operators have long recognized a frustrating variability in reservoir quality within fault blocks of the Lobo trend. Diagenesis of the Wilcox Lobo sandstones is undoubtedly a major control on Lobo reservoir quality, and regional variations in diagenetic processes may explain the differences in reservoir quality observed by the operators. However, published diagenetic studies of the Lobo reservoirs are limited in both areal scope and detail. Moreover, these older studies are have not benefited from some of the recent advances in understanding of diagenesis; the latest study (Alexander and others, 1985) is based on work performed in the early 1980s. Since this last study, many more cores and cuttings from Lobo wells throughout the trend have become available, and there have been advances in understanding of relevant diagenetic processes and research techniques (for example, diagenetic modeling; Giles and de Boer, 1990). Our preliminary analysis of Lobo geology strongly suggests a complex relation among Lobo stratigraphy, structure, and diagenesis that had not been previously noted. A more detailed examination of the regional variations in Lobo diagenesis, for example near fault zones, is warranted.

Previous studies describe Wilcox Lobo reservoirs as predominantly composed of very fine grained, well-sorted sandstones that are mineralogically immature; framework grain composition varies from feldspathic litharenite to litharenite (Railroad Commission of Texas, 1980; Henke, 1982, 1985; Alexander and others, 1985). According to Alexander and others (1985), the most common feldspar grains are orthoclase and albite, and rock fragments are dominantly sedimentary. In selected Lobo 1 and Lobo 6 sandstones, authigenic cements constitute 7 to 15 percent of rock volume, and thin section porosity ranges from 0 to 28 percent (Alexander and others, 1985).

Major diagenetic events observed by Alexander and others (1985) in Wilcox Lobo sandstones from two cores from Webb County are (1) mechanical compaction, (2) cementation by quartz and calcite, (3) dissolution of calcite cement and feldspar grains, (4) precipitation of clay minerals, and (5) fracturing. They recognized two general sandstone classes: (1) massive to laminated, clean sandstones and (2) bioturbated sandstones having abundant detrital clay matrix. Dissolution of calcite cement, feldspars, and rock fragments led to the formation of secondary porosity in clean Lobo sandstones, where most remaining porosity is secondary (Alexander and others, 1985). Kaolinite, chlorite, illite, and mixed-layer illite-chlorite-smectite precipitated in intergranular and secondary pores. Compaction-induced deformation of ductile framework grains and detrital clay matrix occluded most porosity in the bioturbated shaly Lobo sandstones. Thus, clean sandstone, having measured porosities of 12 to 25 percent, forms the primary reservoir rock (fig. 9), but net pay varies widely from well to well. In-situ gas permeabilities range from 0.0003 to 0.5 md generally but locally exceed 1.0 md (Robinson and others, 1986).

Previous studies describe most clean Wilcox sandstones as well sorted and fine grained. In deeply buried Wilcox reservoirs, some evidence suggests that primary porosity has been largely destroyed by quartz and carbonate cementation. The remaining porosity is mainly secondary, resulting from the dissolution of feldspar grains and carbonate cement (Loucks and others, 1986). Cores from several Wilcox wells in Live Oak and Wharton Counties yielded porosities ranging from 2 to 23 percent and permeabilities as high as 10 md (Dutton and others, 1993), although these measurements were made at ambient conditions; in situ values probably are much lower. The relationship of these Wilcox patterns to the Lobo Wilcox trend is unknown. The distribution of porosity-occluding cements and secondary porosity are clearly key issues for Lobo development.

Mujeres Creek Field Lobo Core Description

As part of our review of Lobo geology, seven Wilcox Lobo sandstone samples from one core (Forest Oil Corporation L. Winch-State No. 4, Mujeres Creek field, Webb County) were examined for texture, composition, and diagenetic history using standard thin-section petrography. An additional goal was to compare findings to those of published diagenetic studies. Thin sections were stained for potassium feldspar and carbonates. Point counts (200 points) of thin sections from representative samples from the core were used to determine mineral composition and porosity. Samples were selected from visually clean (minimal detrital clay matrix) and extensively cemented sandstone intervals and are thus representative of Wilcox Lobo reservoir sandstones.

The Wilcox Lobo sandstone samples from this core are uniformly very fine grained. Samples range from poorly to moderately well sorted; most clean sandstones are moderately sorted. Sand grains are angular to rounded.

All Wilcox Lobo sandstones examined are mineralogically immature, and most samples are classified as feldspathic litharenites by the sandstone classification of Folk (1974), although considerable range in composition is evident (fig. 13). All samples are quartz-grain dominated. The average composition of essential framework grains (normalized to 100 percent) from all core samples is 59 percent quartz, 20 percent feldspar, and 21 percent rock fragments ($Q_{59}F_{20}R_{21}$). Plagioclase is the only feldspar observed in the samples, composing from 10 to 15.5 percent of whole-rock volume (table 4). Rock fragments occur in two categories: metamorphic (MRF) and sedimentary (SRF) types. SRFs are the most abundant lithic type and comprise shale, chert, and rare micritic limestone. Low-rank MRFs include phyllite and slate. Mean percentage of whole-rock volume for primary framework grains from the Winch core samples is quartz (38.5), plagioclase (12.9), SRFs (11.3), and MRFs (2.6).

Authigenic cements and replacive minerals collectively constitute between 15.0 and 29.5 percent of the whole-rock volume in the sandstone samples, with a mean value of 22.6

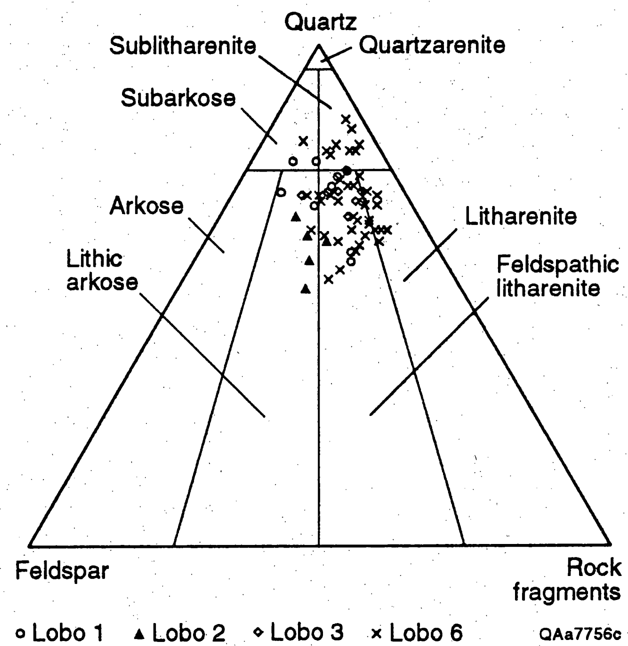



**Figure 13.** QFR (quartz:feldspar:rock fragments) ternary diagram illustrating detrital components of Wilcox Lobo sandstone samples from the Forest Oil Corporation L. Winch-State No. 4 core.

percent. Authigenic quartz, ankerite, chlorite, ferroan calcite, pyrite, and ilmenite occur in Wilcox Lobo sandstone samples. The primary cements (quartz, ankerite, chlorite, and ferroan calcite) have mean whole-rock volumes of 9.9, 6.1, 4.8, and 1.8 percent, respectively.

In the Winch core the primary diagenetic events in the burial history of Lobo sandstones were (1) growth of chlorite rims on framework grains, (2) compaction (roughly contemporaneous with stage 1) causing deformation of ductile rock fragments, (3) precipitation of quartz overgrowths, (4) precipitation of ankerite and ferroan calcite, which filled pores not occluded by quartz overgrowths, and contemporaneous dissolution of feldspars and shaly SRFs and MRFs, and (5) pressure solution and additional silica cementation at quartz-to-quartz grain contacts, probably during deep burial.

The whole-rock volume of chlorite cement varies from 0 to 7.5 percent (table 4). Chlorite, the first cement to form in Wilcox Lobo sandstones, is mostly a grain-rimming cement, but it also fills a small percentage of intergranular pore space (fig. 14).

Quartz cement, on average, is the most abundant cement in all samples, with a whole-rock volume that ranges from 3.0 to 18.0 percent (table 4). Quartz cementation postdated formation of chlorite rims. Quartz cement formed by (1) development of relatively early quartz overgrowths (fig. 15) and (2) additional silica mobilization and subsequent precipitation due to pressure solution between quartz grains during burial compaction. Where quartz overgrowths are abundant, they completely fill some primary, intergranular pores. Generally, in Wilcox Lobo sandstones where chlorite cement is common, quartz overgrowths are relatively rare. Chlorite rims around quartz grains probably acted as barriers to quartz-overgrowth nucleation. Where chlorite is abundant, most quartz overgrowths are small, apparently having nucleated where breaks occur in the chlorite rims. Closed, quartz-sealed microfractures are present in some parts of the quartz cement. In other tight gas formations, such features are useful guides to macroscopic fracture patterns (Laubach, 1989).

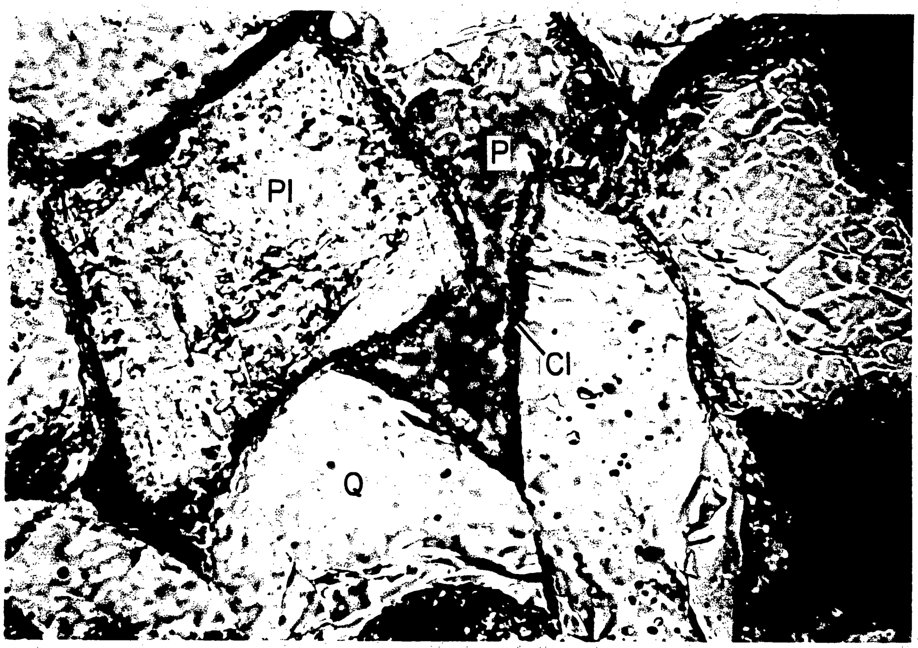



Figure 14. Photomicrograph showing chlorite grain-rimming cement (Cl), primary porosity (P), and quartz (Q) and plagioclase (Pl) framework grains. From Forest Winch-State No. 4 (Lobo 1, 8,869 ft). Horizontal dimension of photo is 0.5 mm.

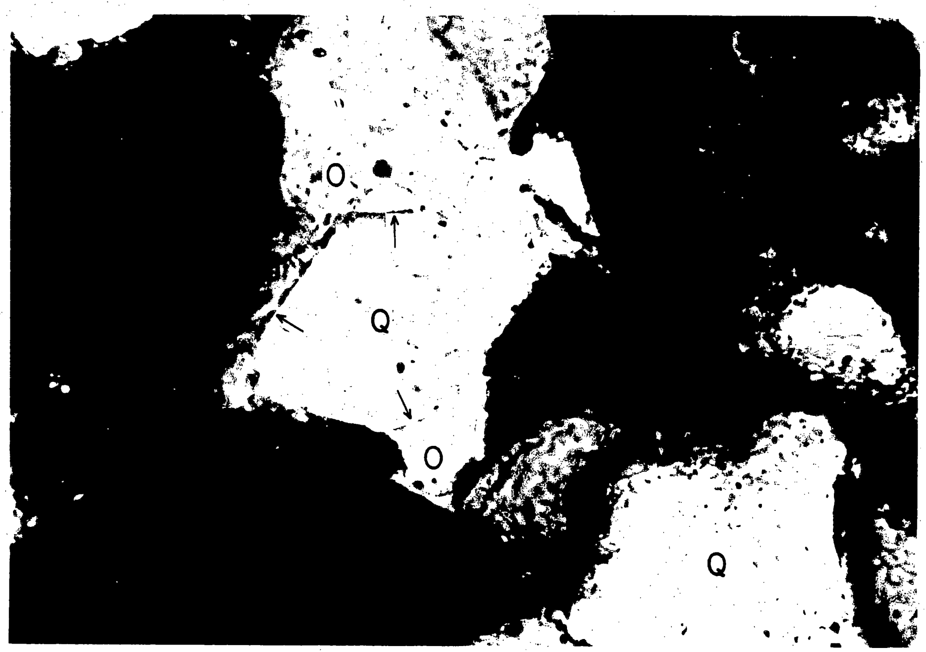



Figure 15. Photomicrograph of well-developed quartz overgrowths (O) growing from relict quartz (Q) grain boundary (arrows). From Forest Winch-State No. 4 (Lobo 2, 9,310 ft). Horizontal dimension of photo is 0.5 mm.

Ankerite, the second most abundant cement in all Wilcox Lobo sandstone samples from this well, has a range of whole-rock volume from 3.0 to 10.5 percent (table 3). Ferroan calcite (fig. 16), another carbonate cement, occurs only in only one of the core samples where it composes to 12.5 percent of the sample (table 4). Ankerite and calcite cements formed late in the diagenetic sequence; textural relations indicate that these cements precipitated after chlorite and quartz cement. Ankerite and ferroan calcite commonly replace framework grains. Partially and wholly replaced feldspar grains are common in sandstone samples from both cores. Completely replaced feldspars appear as relict, rectilinear patches of the carbonate cement. Both carbonate cements also partially replace SRFs and MRFs, primarily shale, phyllite, and slate grains. Complete replacement of shale clasts and MRFs is probable but difficult to ascertain because shale clasts and MRFs typically have irregular grain boundaries. The relative abundance of ankerite, which is present in all the samples, suggests that this cement may also fill intergranular pores that had remained open throughout earlier phases of diagenesis.

Porosity observed in thin section is almost all secondary, which varies from 0 to 14.5 percent (table 4). Average total porosity of samples is 5.5 percent. Cements and ductile, compaction-deformed SRFs and MRFs occlude most visible porosity in the Wilcox Lobo samples. Primary porosity was observed in only one sample and exists as small (several microns) intergranular voids, commonly between quartz grains, and within areas of ankerite and ferroan calcite cement. Secondary porosity is developed as voids within partially dissolved framework grains (mainly plagioclase, shale SRFs, and MRFs) (fig. 17). Average net-overburden porosity, measured by porosimeter, is 18.2 percent in clean Wilcox Lobo sandstones; porosity range is 8.5 to 23.4 percent (unpublished industry data). Thin-section porosity generally is lower than porosimeter porosity because of the presence of micropores between clay flakes and within partly dissolved framework grains. Micropores are measured by a porosimeter, but they cannot be accurately quantified in thin section. Average Klinkenberg-corrected gas permeability measured at net overburden

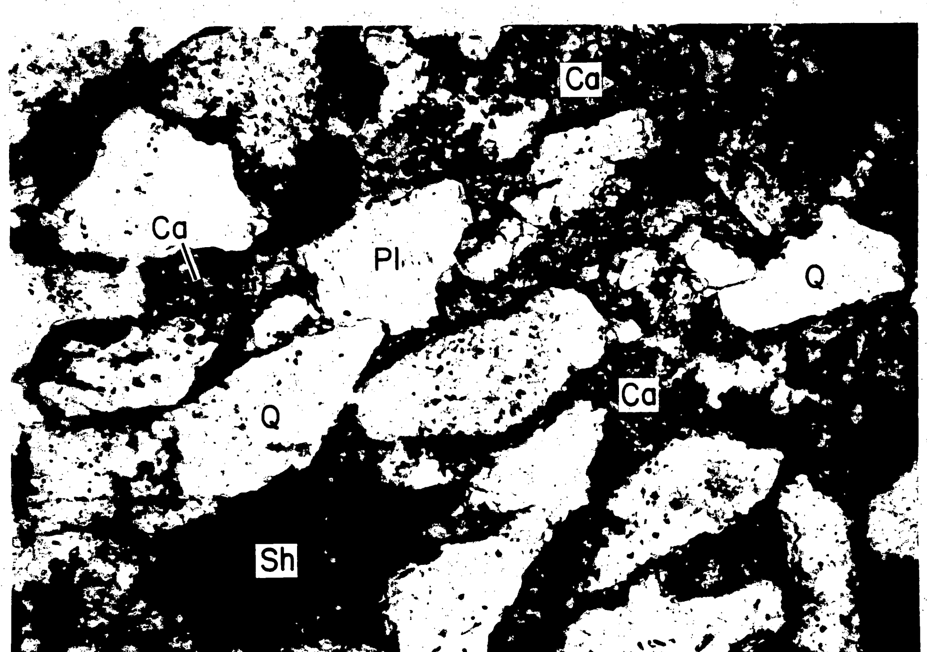



Figure 16. Photomicrograph of abundant, porosity-occluding ferroan calcite cement (Ca) found in some zones of Lobo reservoirs. Framework grains include quartz (Q), plagioclase (Pl), and shale rock fragment (Sh). From Forest Winch-State No. 4 (Lobo 2, 9,327 ft). Horizontal dimension of photo is 1.3 mm.

Table 4. Petrographic analyses of Wilcox Lobo sandstones from the Forest Winch-State No. 4 well, Webb County, Texas. Values given in percent of whole rock volume.

| Constituent (percent) | Range (percent) | Mean |
|---|---|---|
| Framework grains | | |
| Quartz | 29.0 to 45.5 | 38.5 |
| Plagioclase | 10.0 to 15.5 | 12.9 |
| SRF[1] | 7.0 to 16.5 | 11.3 |
| MRF[2] | 0 to 5.0 | 2.6 |
| Other[3] | 0.5 to 2.5 | 1.5 |
| Cements | | |
| Quartz | 3.0 to 18.0 | 9.9 |
| Ankerite | 3.0 to 10.5 | 6.1 |
| Chlorite | 0 to 7.5 | 4.8 |
| Fe-calcite | 0 to 12.5 | 1.8 |
| Matrix | 0 to 12.0 | 5.1 |
| Primary porosity | 0 to 0.5 | 0.1 |
| Secondary porosity | 0 to 14.5 | 5.4 |

[1]Sedimentary rock fragments
[2]Metamorphic rock fragments
[3]Mostly pyrite, ilmenite, and various heavy minerals

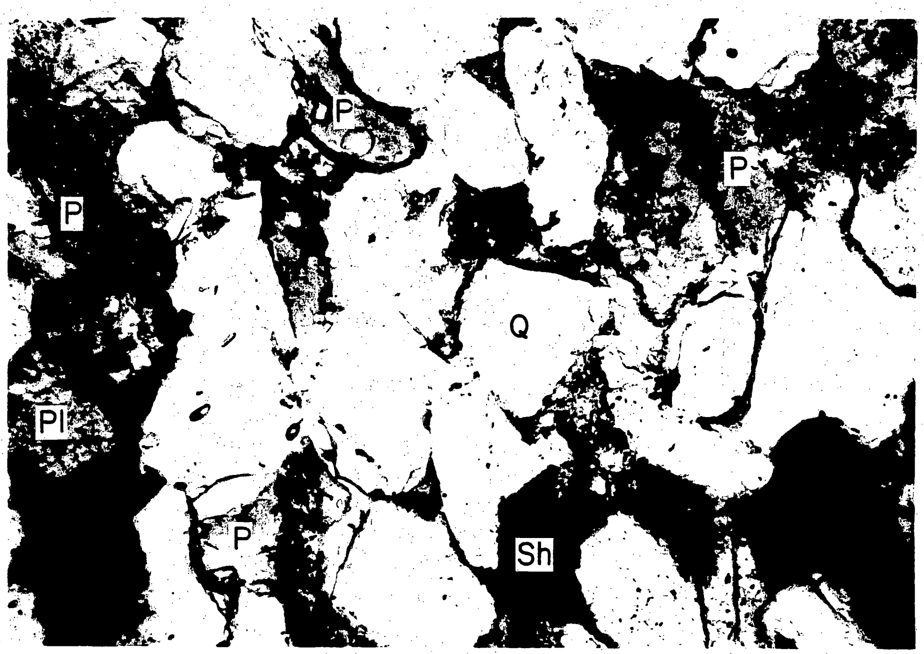



Figure 17. Photomicrograph of abundant secondary porosity (P) produced by dissolution of clay-rich rock fragments. Framework grains include quartz (Q), plagioclase (Pl), and shale rock fragment (Sh). From Forest Winch-State No. 4 (Lobo 2, 9,330 ft). Horizontal dimension of photo is 1.3 mm.

pressure for the Wilcox Lobo sandstone samples is 8.02 md and ranges from 0.01 to 40.7 md (based on compilation of unpublished industry data).

Findings of the core study generally agree with those of Alexander and others (1985); some minor differences may be due to the selective inspection of clean sandstones in this single-core study. However, they observed orthoclase in Lobo samples, whereas none were observed in our core study. Selective dissolution of orthoclase with depth in Tertiary Gulf Coast sandstones (Land and others, 1987) may explain this variation between the two studies, and suggests that feldspar dissolution may be more variable within the Lobo trend than published reports portray. Alexander and others' (1985) shallower core samples may contain relict orthoclase. Orthoclase dissolution can potentially contribute to increased porosity in sandstones, although the simultaneous precipitation of reaction products (quartz, kaolinite) in nearby pore space may prevent significant change in total porosity of reservoir rocks (Giles and de Boer, 1990).

Reservoir Quality and Completion Practices

Petrographic analysis of the Forest Winch core and unpublished industry data show a complicated diagenesis that can be generalized into a diagenetic sequence (as described in a previous section of this report). However, several observations suggest that this diagenetic sequence may be quite variable in different areas of the Wilcox Lobo trend. Cement volumes in sandstone samples from the Forest Winch core differ vertically within each reservoir zone. This apparent bed-to-bed zonation of cements suggests a complex process of diagenesis related to preferred fluid flow in more permeable strata, multiple generations of intrastratal fluids with varying chemistries, and/or subtle vertical differences in sandstone framework-grain constituents whose dissolution products would influence cement mineralogy. Diagenetic trends such as depth versus cement volume or depth versus porosity and permeability, important predictors of regional reservoir quality, are obscure in the Lobo trend. Therefore, controls on reservoir quality in the trend are probably not a simple function of depth.

Diagenetic processes and reservoir quality could be ultimately controlled, at least in part, by proximity to faults and fractures caused by one of several phases of faulting. In faulted areas, for example, the paragenetic sequence could be more variable than in rocks that are undeformed, depending on whether the fault is leaky or tight. Such a determination could possibly be made or tested by regional formation-pressure mapping (see below). Effects of geopressure on formation-water migration and rock/water interactions may also have a subregional influence on diagenesis in Lobo reservoirs. Lobo operators have observed that petrophysical properties of Lobo sandstones vary among individual fault blocks in the trend. Determining the diagenetic controls on these petrophysical properties within individual fault blocks is considered to be a major challenge by the operators.

Giles and de Boer (1989) described a diagenetic process that could be analogous to that which characterizes faulted areas of the Lobo trend and that possibly helps explain the suspected complex diagenetic patterns in the Lobo reservoirs. Their theoretical model assumes that some major faults act as relatively chemically inert fluid-escape pathways that drain more deeply buried parts of a sedimentary basin, similar to faults described by Burley (1986) in North Sea fields. As formation waters originating at depth that are in chemical equilibrium with a carbonate mineral rise along the faults, fluid temperature decreases and the water becomes undersaturated with respect to that mineral. At an impermeable zone along the fault, perhaps where shale is faulted against shale, formation waters are channeled into reservoir rock where the carbonate-undersaturated waters would cause extensive carbonate leaching, thereby potentially improving the reservoir quality locally along the fault. Thus, in the Lobo trend calcite may locally predominate as a cement near faults and show evidence of several cementation events as a result of episodic upward fluid movement along faults (leaching events) (fig. 18). Alternatively, leaching of silicate minerals in reservoir rock along deep-seated faults may occur from contact with rising hydrothermal solutions (Riches and others, 1986). Alam and others (1986) found that the driving mechanism for the upward migration of hot formation fluids along faults of onshore Louisiana is the higher pressure of an underlying

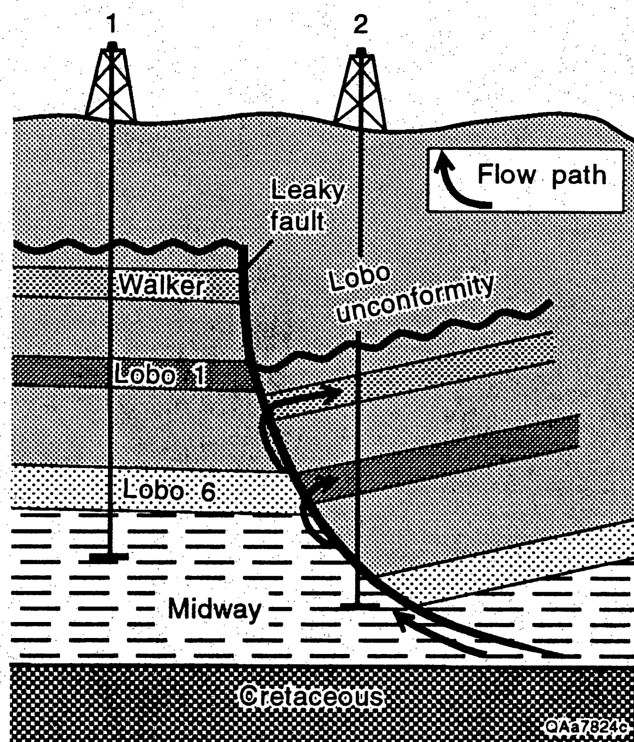



**Figure 18. Schematic cross section illustrating upward migration of formation waters along a leaky fault and channeling of waters into Wilcox Lobo reservoir zones. This process may be responsible for the considerable variation in diagenetic characteristics that Lobo operators have noted across the trend.**

overpressured section, similar to that in the Lobo trend. In some areas of the Lobo trend, zones of secondary porosity in reservoir rock correspond to zones of abnormal pressuring in adjacent shales (Alexander and others, 1985). These hypotheses could be readily tested with a suite of whole or sidewall cores taken at various positions relative to faults.

Cement volumes in samples from the Forest Winch core are highly variable within and among reservoir zones, perhaps a characteristic throughout the Lobo trend (table 4). This observation has important implications in designing completion strategies. For example, zones within reservoirs that have abundant iron-rich chlorite cement would be extremely sensitive to the use of hydrochloric acid (HCl) during completion of a well. In the presence of HCl and oxygenated water, chlorite readily dissolves and the iron liberated will precipitate as gelatinous ferric hydroxide, an effective pore-clogging compound (Almon and Davies, 1978). This problem can be avoided if the chlorite-rich zones are known and an appropriate iron-chelating agent and oxygen scavenger are used. With a regional core data base and diagenetic models, intra-reservoir areas with higher potential for production and with particular characteristics that would affect completion practices could be mapped, thereby aiding the operator in more effectively and efficiently producing from Lobo reservoirs.

## Compartment Structural Geometry

The entire Wilcox Lobo trend is highly faulted (figs. 10, 19). Missing sections result from faulting, truncation by a major regional unconformity, and truncation by several local unconformities (Railroad Commission of Texas, 1991).

- Identifying and mapping large faults is one issue of concern to operators. Regional geologic studies can aid 2-D and 3-D seismic studies of such faults, so that seismic surveys can be concentrated in critical areas.
- Faults that are too small to be detected with seismic methods are another concern. Such features can be documented with core and geophysical well log studies and predicted with modeling methods.

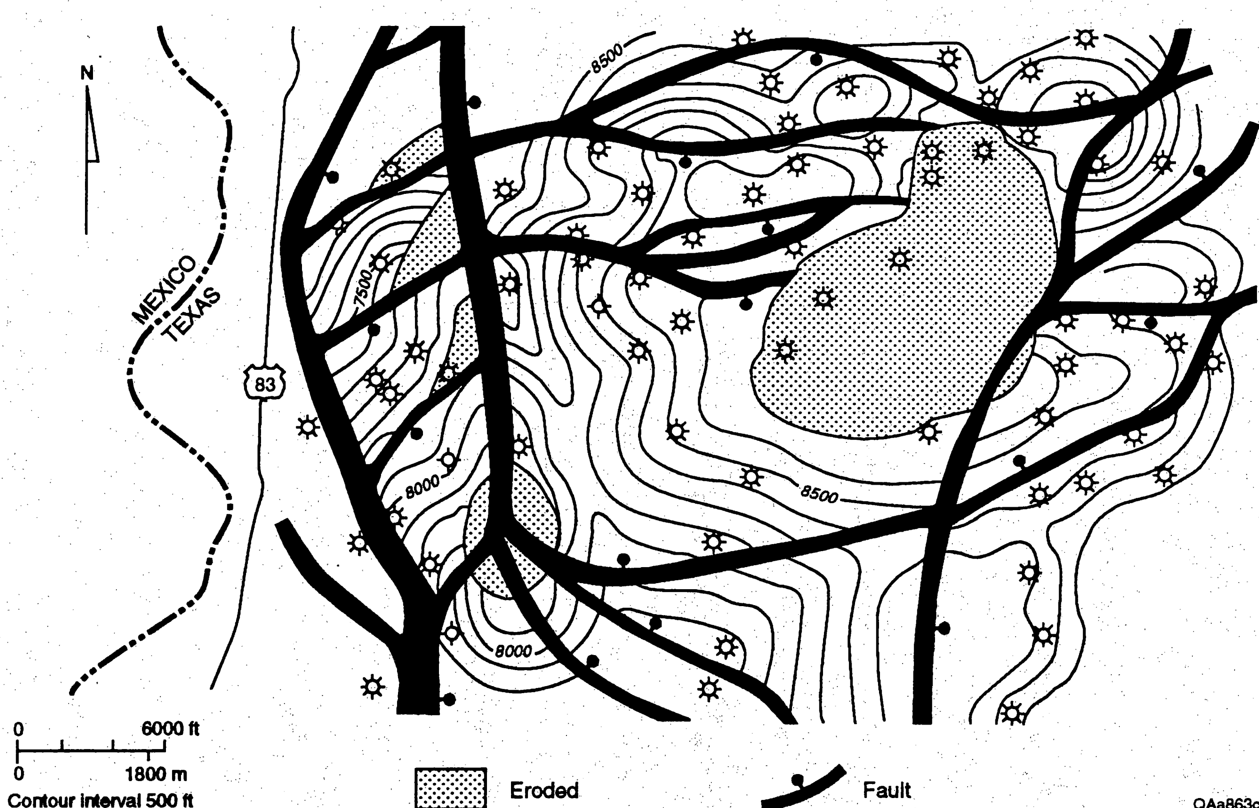



Figure 19. Structure map of faulted Wilcox Lobo reservoir (Lobo 1, J. C. Martin field, Zapata County). From O'Brien and Freeman (1979).

Faulting in the Wilcox Lobo has been ascribed to large-scale gravity sliding accompanied and followed by extensional faulting at various scales (Long, 1986). Subaerial or subaqueous erosion, or both, created pronounced unconformities, locally truncating productive sandstone. At least one episode of faulting followed the period of erosion (Railroad Commission of Texas, 1980; Robinson and others, 1986). Repeated faulting and erosional truncation has made accurate prediction of the size and distribution of reservoir sandstones difficult (Railroad Commission of Texas, 1980; Henke, 1982, 1985).

Traps in the Lobo trend are bounded by normal faults and, locally, subsidiary faults that repeat section (apparent reverse faults). Fault geometry and fault patterns cannot always be adequately resolved even with 3-D seismic information. Some fault blocks are extremely small, creating pressure compartments of less than 80 acres (Robinson and others, 1986). Published geologic cross sections and maps are highly simplified and probably are not representative of structural and stratigraphic heterogeneity in this unit. For example, the number of recognized faults in some cases is proportional to well density (fig. 20) illustrating the difficult of positive fault identification prior to drilling. Consequently, projection of production performance and reserves in a highly faulted area like the Wilcox Lobo trend is challenging. The range of fault-block sizes and fault-related flow baffles that are expected in this structural setting are a reason to infer numerous remaining small fault compartments in the Lobo. Such features are generally not uniformly distributed within faulted areas, but their location may be predictable (figs. 21, 22).

Displacements across major faults within the trend are commonly as much as 700 to 1,000 ft. The major producing zones are in a stratigraphic section that is commonly no more than 1,000 ft thick, so the location of faults can be critical for governing the presence of reservoir sandstones and defining the size and shape of fault-bounded targets.

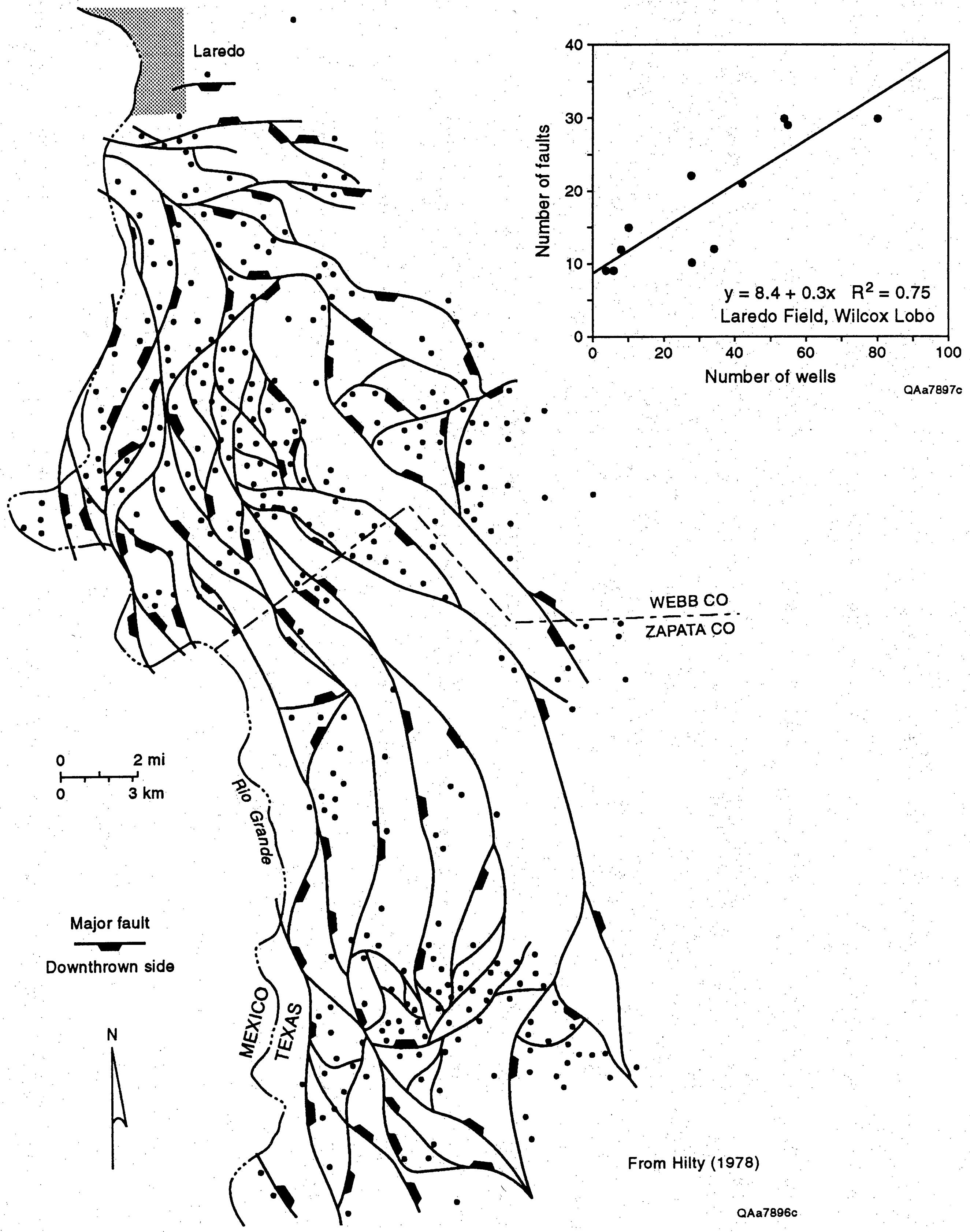



Figure 20. Fault map and fault-density patterns in Laredo field.

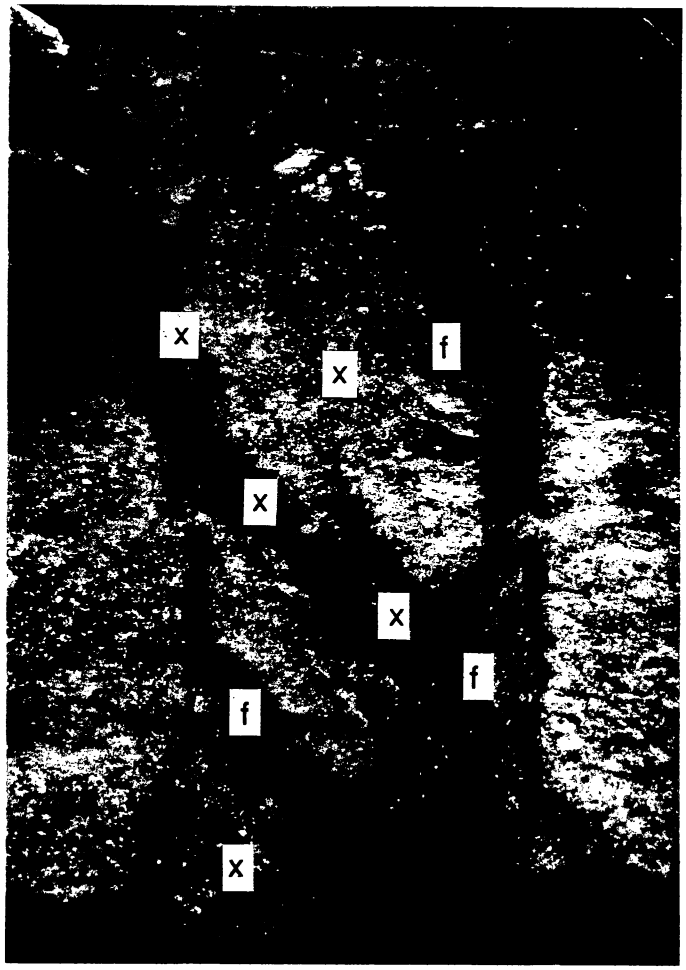
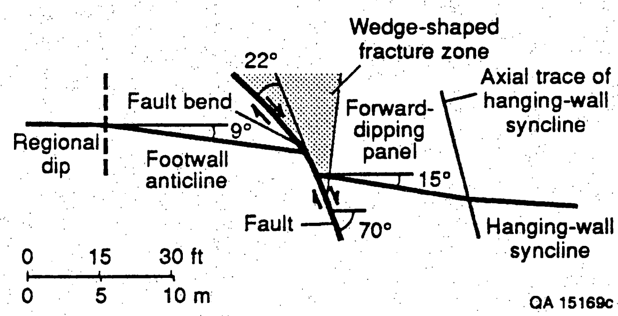



Figure 21. Outcrop example of normal fault "compartments" (x) near the termination of a master fault (f) illustrating how small and large fault blocks can be genetically associated. In the Lobo, fault-bounded compartments that are near the margins of current drilling targets may be accessible in the future with directional drilling. From Laubach and others (1992).

(a)




(b)

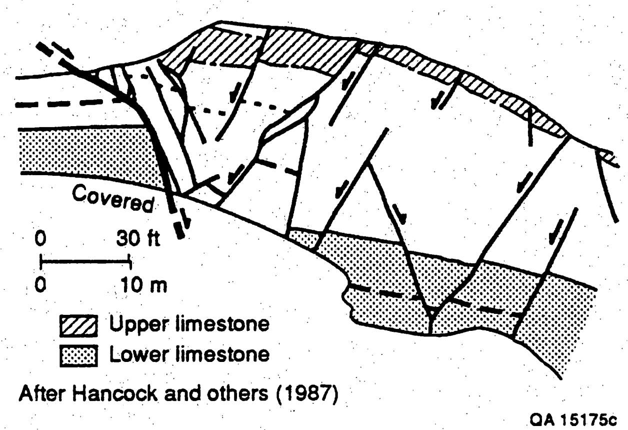



Figure 22. Cross sections showing two examples of fault zones localized near curved fault planes. (a) Generalized example showing main geometric elements. (b) Example from Arabian shield. Lobo faults are curved in both plan view and cross section. Fault plane maps could help identify areas where fault-bend curvature has produced subsidiary fracture porosity and small traps.

Recognizing faults and fault patterns is a key issue in Lobo development. The use of 2-D and 3-D seismic data is reported by operators to be critical for identifying the extent of fault blocks. Subdivision of such fault blocks by small-scale faults that are below the resolution of seismic data is considered by some operators to be a common phenomenon that can produce barriers and baffles to flow within large fault blocks, but currently such features are not accounted for in development and completion design.

Fault density is variable but commonly high. O'Brien and Freeman (1979) reported that only about 23 percent of wells lacked significant missing section, but the number of wells affected by faulting may be much higher. Anecdotal reports from operators suggest that as many as 90 percent of Lobo wells may have significant missing or repeated section as a result of faulting. Regional Lobo fault patterns have variable strike. In the western part of the play westward-tilted fault blocks bounded by northwest-striking, down-to-the-coast normal faults are evident on published seismic lines (O'Brien and Freeman, 1979), but dominant trends on published schematic maps shift to more northeasterly strikes in the northeastern part of the trend. Reservoir-scale fault and fracture orientations, slip patterns, and density are highly variable (e.g., Self and others, 1986a, b).

Faults are currently recognized based on seismic information, missing or repeated section on well logs, and evidence from dipmeter and borehole-imaging logs. In addition to fault gouge material and breccia, abrupt shifts in bedding dip are one manifestation of faulting and fault-block rotation that has been noted in Wilcox Lobo core (Railroad Commission of Texas, 1980). Local areas where bedding dips range from nearly flatlying to subvertical have been noted. In the absence of core, such shifts in bed dips can be mistaken on dipmeter logs for sedimentary structures such as cross-bedding, resulting in misleading views of reservoir architecture. Soft-sediment-deformation features are also evident, including tight recumbent folds, microfaults, and vertical beds. Some of these features may be entirely contained within large slump blocks (Railroad Commission of

Texas, 1980). Borehole-imaging geophysical devices are becoming increasingly important tools for recognizing and documenting such features.

Normal faults with throws of 50 ft or more have been mapped in most Lobo trend reservoir intervals, and the prevalence of such mappable faults is an indication that smaller faults and fractures that are below the resolution of seismic detection are locally abundant in reservoir rocks. Some Wilcox Lobo reservoirs are reported to be extensively microfaulted (Railroad Commission of Texas, 1980). In these areas, small, steeply to shallowly dipping normal faults (millimeter-scale fault displacement) are said to be arranged in horst-and-graben patterns. In other normal-faulted areas, large faults are commonly associated with numerous smaller faults and fractures (Walsh and Watterson, 1988; Laubach and others, 1992) that may subdivide and compartmentalize reservoir rocks at scales below typical map scales or seismic resolution. Evidence of the size and frequency distributions of faults that are below the resolution of 3-D seismic (less than 50 to 100 ft throw) was cited as information that would be useful to engineers designing methods to exploit such features. Physical models and small-scale fault patterns in outcrop show that aspects of fault orientation and intensity can be predicted through structural modeling (figs. 22, 23; Laubach and others, 1992). Accurate predictions of fault patterns would be useful for guiding advanced Lobo directional drilling programs, where the drilling system must respond to frequent fault discontinuities.

Faults of different ages, origin and orientation may play differing roles in controlling reservoir properties, and operators cite identifying the age of faults as a parameter of interest for this reason. All faults do not extend through the entire section; locally some early (syn-sedimentary) faults do not extend to the top of the lower Wilcox interval (Railroad Commission of Texas, 1991). The number of fault generations affecting the Lobo is uncertain. Map patterns suggest that several fault generations have influenced the Lobo trend, and that published accounts do not fully account for fault patterns. The relative age of faults in a given area can be ambiguous based on

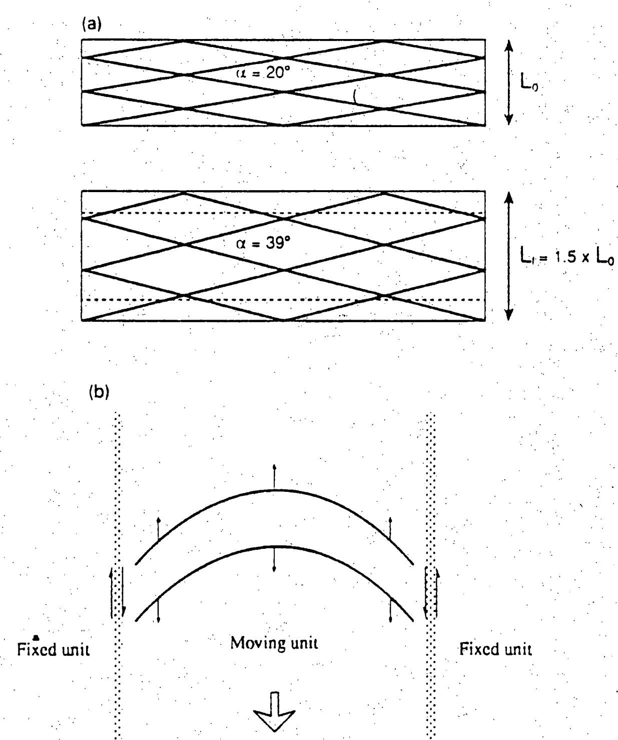



**Figure 23. (a) Increase in obliquity between fault traces induced by uniform uniaxial stretching (map view). (b) Fault trace curvature induced by lateral friction. From Laubach and others (1992) after Vendeville (1987).**

conventional subsurface map and 2-D seismic patterns. This ambiguity introduces uncertainty in interpretation of fault and fault block—and thus trap—attributes.

Direct observations of fault-zone material have not been reported for Lobo trend rocks, but such information could shed light on the role of faults and seals or fluid conduits. Where faults postdate sedimentation, fault-related grain crushing and compaction can be expected to have altered (increased or decreased) porosity and permeability along fault surfaces (Knipe, 1992). Synsedimentary and postdepositional faults are likely to have differing microstructure that will affect how they transmit or impede fluid flow. In the Lobo structural setting, numerous small faults and fractures can be expected that can either enhance or detract from reservoir permeability and continuity (Laubach and others, 1992). Processes that reduce grain size and porosity along faults can result in permeability barriers, even where small-displacement faults result in sandstone-on-sandstone contacts across faults (Knipe, 1992).

No systematic published information is available on core-scale natural fractures and faults in Wilcox Lobo reservoirs, yet our core observations and Railroad Commission reports show that such features are present (Railroad Commission of Texas, 1980). Petrographic surveys of Wilcox Lobo sandstone cores show that sealed and open microfractures are locally present. Currently fractures are not targets of Lobo drilling programs. Together with widespread evidence of faulting in Lobo Wilcox reservoirs, these observations suggest that systematic study of small-scale features in core could provide useful information on fracture density and possibly proximity of boreholes to faults.

Quartz cementation is prevalent in some Wilcox Lobo sandstones, and if fracturing accompanied quartz precipitation some fractures may tend to be held open by quartz that partly fills fractures despite high closure pressures encountered in some deep wells. Information on fractures (vein) crosscutting relations and vein mineral fill could shed light on relative age relations among faults, fractures, and cements and could lead to appropriate strategies for targeting wells within fault blocks that are segmented by faults that are too small to be resolved by seismic methods. Preferred fracture orientation may also cause flow and rock strength anisotropy. Such information is important for hydraulic fracture treatment design in areas where the treatment target is small relative to the potential size of the created fracture, because of the potential for unexpected growth-out-of-zone and development of near-wellbore tortuosity.

Fractures and cracks at all scales are common in crustal rocks, and in view of the widespread development of faults in the trend, the Lobo is no exception. Nearly every physical property of crustal rocks, such as response to applied loads, hydraulic, thermal, and electrical conductivities, and seismic properties is determined to some extent by these small fractures and the fluids they contain. Physical properties of reservoir rocks and nearby nonreservoir shales and mudstones need to be measured or accurately estimated in order to prudently design hydraulic fracture treatments and simulate reservoir behavior. Yet hydraulic fracture treatments are typically designed and executed without information on natural fracture attributes, despite evidence that these features are likely to be widespread in the Lobo. The success of many engineering operations—and particularly hydraulic fracture treatment and extraction of gas from naturally fractured reservoir rocks—depends on an understanding of orientation, character, and distribution of fractures.

## Fluid Pressure, Fluid Flow, and Stress Patterns

Fluid pressure, fluid flow, gas chemistry, and stress patterns are key elements of any regional natural gas play description. Currently, for the Lobo play, published information on all of these topics is sparse. In this section, we briefly describe how such information is relevant to Lobo development issues.

### Formation-Pressure Maps

Accurate regional maps of Wilcox Lobo formation pressures and temperatures are currently unavailable. However, knowledge of the pressures of reservoir facies is vital to the exploration and development of natural gas. Gas moves toward and accumulates in subsurface areas having lower excess pressures (Hubbert, 1953). The pressure of fluids in pore space affects both porosities of sedimentary rocks and velocities of seismic waves used to examine geological structures in the subsurface (Dutta, 1987). Thus, pressure information is important in areas such as the Lobo trend where 3-D seismic surveys are carried out. Pressure information is a key component in the design of hydraulic fracture treatments and implementation of advanced hydraulic fracture treatment design models. Drilling and other reservoir engineering activities are also affected by pressure conditions. Background information on pressure patterns and an adequate model of the causes of pressure patterns may lead to better predictions of high producibility zones within the trend.

Pressure can vary gradually or abruptly on a local to regional scale and can provide key information on the location and areal distribution of reservoir compartments (Bradley, 1975; Hunt, 1990). Regional maps of formation pressures of the Lobo trend and geological modeling and prediction of pressure patterns have several potential practical uses (e.g., Bair and others, 1985):

- delineating formation-pressure discontinuities that represent potential faults or other permeability barriers,
- finding areas of highest formation pressures (pressure anomalies), which may identify separate structural and stratigraphic compartments,
- differentiating relatively high-permeability pathways from areas of low permeability (fig. 24), and
- determining directions of fluid (water and hydrocarbons) flow within each fault block (fig. 24).

Formation pressures can be mapped on a regional scale using conventional bottom-hole pressure measurements and/or drill-stem tests (Bredehoft, 1963; Bair and others, 1985; Kaiser and others, 1994), among others. Drill-stem test data can be plotted as a

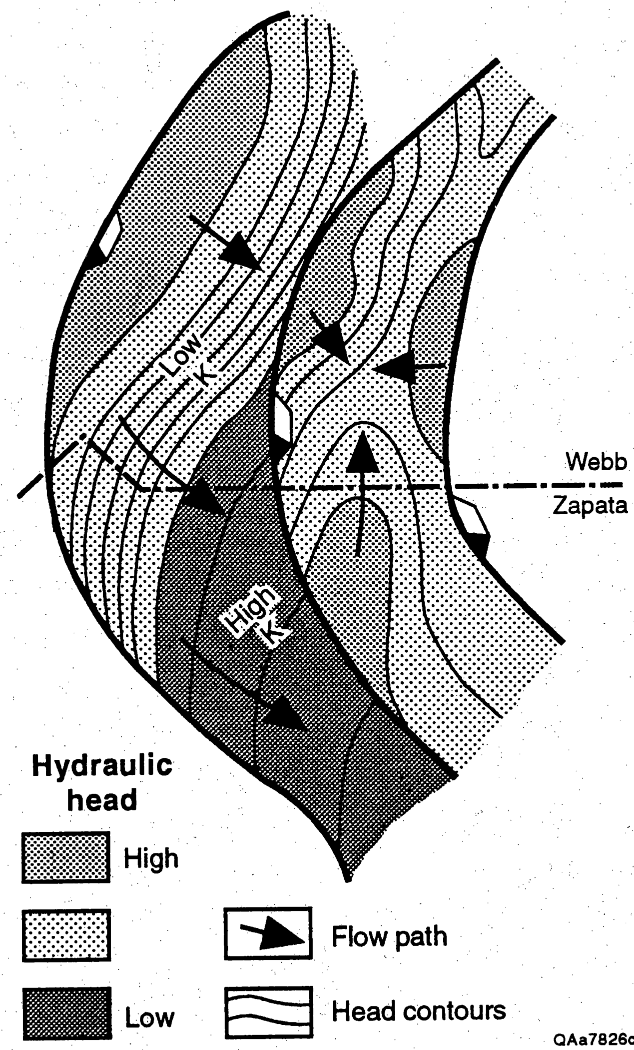



Figure 24. Conceptual regional map of formation pressures (potentiometric surface) in the Lobo trend. Such maps have the potential to identify faults and other permeability barriers, and pressure anomalies, which may represent isolated reservoir compartments. Areas of closely spaced head contours indicate steep hydraulic gradients and thus lower conductivity (K), or permeability, whereas more widely spaced contours indicate higher conductivity. Flow lines, by definition, are perpendicular to head contours.

function of depth and converted to hydraulic head values, which can then be contoured. Hydrodynamic modeling and burial history analysis can also be used to predict pressures (Dahlberg, 1982; Mann and Mackenzie, 1990).

Pressure anomalies that have steep lateral potentiometric head gradients (thousands of feet of head difference) across narrow horizontal distances (hundreds to thousands of feet) could reflect compartments separated by impermeable barriers (Bradley, 1975; Hunt, 1990). In the Lobo trend these barriers are probably mostly faults, which are so abundant in the trend (fig. 24). There are several key questions about Lobo trend reservoirs that regional pressure and stress direction mapping may help answer.

- Are there regional patterns in pressure or stress directions?
- Are Lobo fault blocks hydrodynamically isolated from adjacent rocks and characterized by a lack of hydrodynamic flow?
- What are the dimensions of pressure compartments?
- Which faults sets in the trend (if any) are seals?
- Which faults (if any) are master faults for fluid flow?
- Are several types of seals represented (shale caps, diagenetic fronts, faults, etc.), and can they be distinguished and predicted?

Acquisition of a regional data base of formation pressures would clarify these and other questions.

### Hydrochemical-Facies Maps

Mapping of chemical facies in subsurface formation waters is a useful method of determining areal distribution and location of potential flow barriers (stratigraphic facies changes, diagenetic fronts, sealed faults) and reservoir compartments and regional directions of fluid flow. As such, it is a method that is complementary to formation-pressure mapping.

Hydrochemistry is particularly useful for delineating flow patterns if pressure head data are sparse or ambiguous. Because hydrochemistry reflects rock/water interaction and the prevailing formation-water flow rates and directions, a hydrochemical map indicates formation-water circulation patterns through distribution of mass (dissolved solids). In contrast, a formation-pressure (potentiometric-surface) map indicates circulation through distribution of potential energy. In other words, chemical composition records actual formation-water movement (mass transfer), whereas hydraulic head shows the direction of force that drives formation-water flow. Regional trends in hydrochemistry are mappable and vary in a reasonably predictable fashion along flow paths in some basins (Fogg and others, 1991; Kaiser and others, 1994).

In a conceptual example of a regional hydrochemical map of the Lobo trend (fig. 25), chlorinity variation is shown because it is a conservative chemical species that is relatively unaffected by rock/water interactions. Therefore, the absolute regional changes of chlorinity concentration would be minimal and could be accurately and realistically mapped and interpreted. For example, within the fault block on the left side of figure 25, formation-water flow is depicted as down hydraulic gradient from low to high chlorinity areas. Flow occurs perpendicular to isohalines. Locally marked chlorinity contrasts across narrow zones define interpreted flow barriers (in this example, faults). In the fault block in the right part of figure 25, pockets of high chlorinity adjacent to faults perhaps reflect upwelling of high-chlorinity waters locally along the faults. Flow convergence, as defined by the hydraulic gradient, identifies a potential area for fluid (including hydrocarbon) accumulation. Results of hydrochemical facies mapping also have application to well log interpretation through regional and local prediction of salinity patterns.

At the subregional scale, pressure and geochemical data can be used together (fig. 26) to give better resolution of fault-bounded compartments at the step-out scale and to help confirm fault locations that are resolved on 3-D seismic. In the hypothetical example shown in figure 26, formation-pressure data define three pressure (head) domains within an area bounded by two master faults. Contrasts in formation pressures across secondary faults may not be as pronounced as those across the master faults. However, pressure

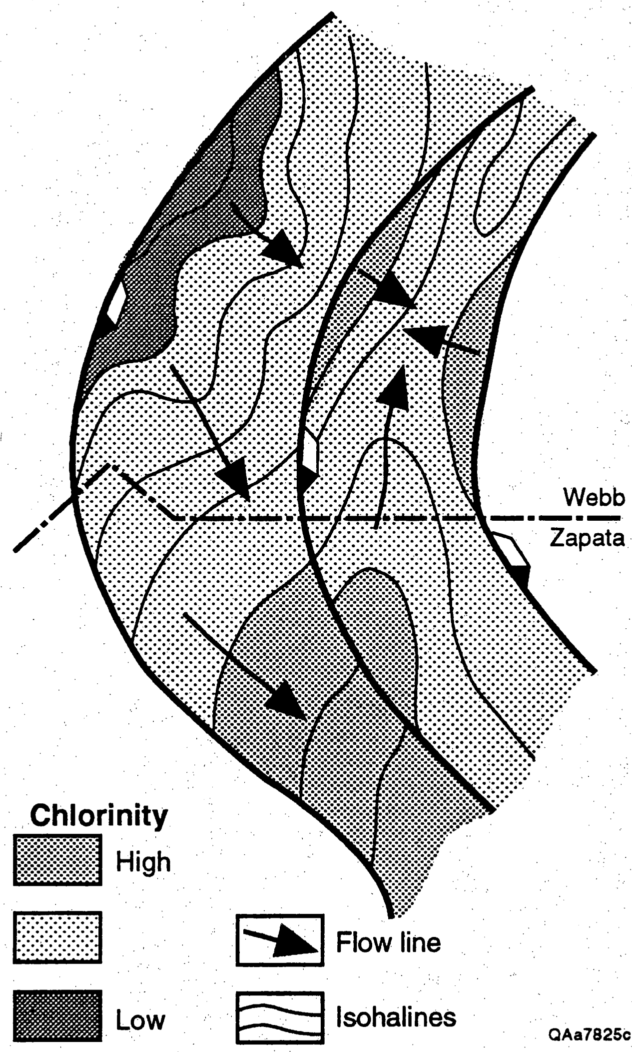



Figure 25. Conceptual regional map of chlorinity in the Lobo trend. Use of this mapping technique with formation-pressure mapping would be a potentially effective means of more clearly delineating regional fault trends in the Lobo area. Water flow can be both toward and away from areas of higher salinities, but it is always perpendicular to isohalines.

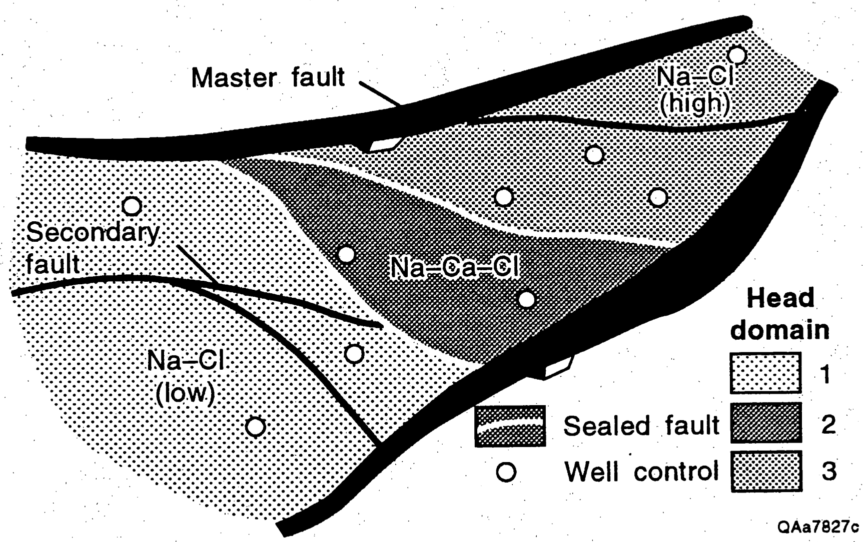



Figure 26. Conceptual subregional map illustrating the combined use of hydrochemical-facies and formation-pressure (head domains) data to locate reservoir compartments at the step-out scale in the Lobo trend.

compartments in the region between the master faults could be confirmed with hydrochemical data. In figure 26 the variation in the assemblage of ionic species defines a sealed fault-bounded compartment containing an Na-Ca-Cl facies, in contrast to the adjacent internally fault-segmented areas where no Ca is present. This degree of resolution of potential reservoir compartments in the Lobo trend would be especially useful to operators with limited and/or widely scattered lease acreage.

Gas-Composition Maps

Natural gas composition can vary significantly within individual fields, both vertically among formations and laterally between wells, but such variation has not been documented in the Lobo trend. In general, where this phenomenon has been observed, this variability is commonly an indicator of reservoir compartmentalization (Smalley and England, 1994) and can be used with formation-pressure and hydrochemical data to better define reservoir heterogeneity. There are several parameters that collectively or individually enable mapping of regional gas-composition distribution, including carbon dioxide compositional trends, the gas wetness index ($C_2$-$C_5$/$C_1$-$C_5$ ratio), and the gas dryness index ($C_1$/$C_1$-$C_5$ ratio). This technique has been used most extensively in studies of coalbed gases in basins of the western United States. The areal occurrence of coalbed gases in the San Juan Basin of New Mexico and Colorado have been characterized using the gas dryness index (Scott and others, 1991) (fig. 27). Here, coal gases are considered to be very dry if the $C_1$/$C_1$-$C_5$ ratio is >0.99; dry gases have values between 0.94 and 0.99; wet gases have values between 0.86 to 0.94; and very wet gases have values less than 0.86. Similarly, carbon dioxide in coal beds is variably very high (>10 percent), high (96 to 10 percent), moderate (2 to 6 percent), and low (<2 percent) (Hanson, 1990).

In this illustration, evaluating and mapping gas-composition data from individual wells allow regional compositional trends to be evaluated, and when used in conjunction with gas isotopic data, multiple gas origins and/or reservoir compartmentalization may be determined. Regional compositional distribution is commonly influenced by regional

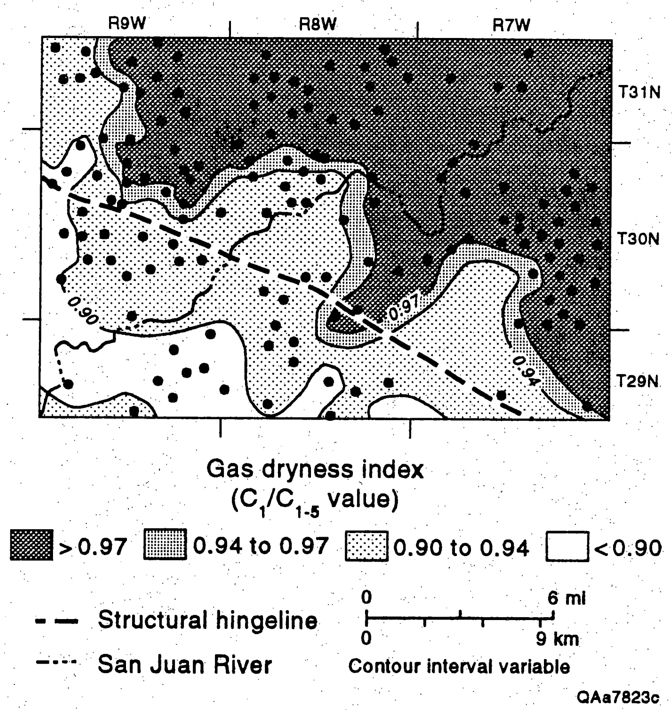



Figure 27. Example of a gas-composition map of the San Juan Basin in which the gas dryness index is contoured. Trends in these maps, like those in formation-pressure and hydrochemical maps, commonly mirror regional structure in the mapped areas and are thus potentially useful to Lobo operators in differentiating separate fault blocks in the complex Lobo trend. Modified from Scott and others (1991).

structure (fig. 27). Compositional heterogeneity in coal gases from the Fruitland Formation in the San Juan Basin is closely related to basin hydrogeology and average daily production (Scott and others, 1994). Significantly, Schoell and others (1994) demonstrated that gas compositional variability in individual fault blocks within reservoirs is due to mixing of biogenic and thermogenic gases. Pictured Cliffs Sandstone gas-composition variability in the San Juan Basin is attributed to mixing of gases derived from overlying coal beds and the underlying Lewis Shale (Scott and others, 1991). In some areas of the Pictured Cliffs high-productivity fairway, there is a direct correlation between gas composition and initial gas potential (Scott and Ayers, in review). Although specific findings from these studies are unlikely to apply to the Lobo trend, the methods described are potentially useful.

Gas-composition mapping has not yet been applied to the Lobo trend, but Lobo operators believe that this technique would be useful on a regional scale to better define fault blocks in the trend. Some operators report that they do not observe significant differences in gas composition within individual fields, although a systematic mapping program using gas dryness index, gas wetness index, and carbon dioxide compositional trends in concert may be sensitive enough to resolve intra-field variations (potentially interpretable as compartments) that the operators have not adequately resolved with current approaches. Operators also noted that gas-composition mapping would be especially valuable in determining the reasons for observed variations in gas condensate volume, an economically important issue.

### Stress-Direction Maps

Because the propagation of hydraulic fractures, physical properties of reservoir rocks, and stability of uncased wellbores are influenced by in situ stress state, it is important to map the orientation of principal stresses in gas-bearing regions, as well as to determine in situ stress magnitudes. No regional or field-scale maps of stress patterns in the Lobo play have been published, and no published Lobo stress profiles are currently available.

The Wilcox Lobo play is interpreted to be in the Southern Great Plains stress province, a transitional province between the Mid-plate compressional province and the Cordilleran extensional province (Zoback and Zoback, 1989). The Lobo play is also near the transition to the Gulf Coast extensional province. The Southern Great Plains province is a boundary zone between the active extensional tectonism of the western Cordillera and the uniform compressional patterns of the midplate region of the eastern and central United States. Shifts in stress orientation characterize the Southern Great Plains province, and although the pattern on the stress map of the United States is generalized, it shows a shift in maximum horizontal stress from northwest to west-northwest in the vicinity of the Lobo play. Nevertheless, the closest published modern stress direction measurements in reservoir rocks to the Lobo trend are from a study of borehole breakouts in Vicksburg reservoirs in McAllen Ranch field, where Langford and others (1992) found east to northeast $Sh_{max}$ directions. Northeast-trending $SH_{max}$ is also shown in Mexico along the U.S.—Mexico border and east of the Lobo play in Texas (Zoback and Zoback, 1989). Published regional stress patterns are therefore not adequate to predict stress directions in the Lobo or to predict the stress regime that governs stress magnitudes.

There are further reasons to question whether published regional-scale stress information is an adequate guide for engineering design in the Lobo. In highly faulted areas such as the Lobo play, stress directions, fluid pressure, and stress magnitudes could shift from fault block to fault block. Previous studies in faulted areas show that such shifts can be abrupt. This suggests that a need exists for stress maps of the Lobo play at a finer resolution than those of published accounts. Maps should have sufficient data points to document regional patterns, as well as information appropriate to test variability in stress orientation among fault blocks and at subregional scale.

Mapping principal stresses in the Lobo play should be feasible, given the play-wide use of dipmeter logs. Directions of principal stress orientations can be determined by identifying stress-induced wellbore breakouts from uncomputed four-arm caliper dipmeter logs (Bell and Gough, 1979). Wellbore breakouts, among the most reliable phenomena for determining stress directions, are symmetric, spalled regions around the borehole wall that are aligned with the minimum horizontal stress (Bell and Gough, 1979; Gough and Bell, 1982). Breakouts can be identified on dipmeter logs, the quality of breakout data gauged, and appropriate cutoff levels for mapping breakouts determined (Plumb and Hickman, 1985; Baumgardner and Laubach, 1987).

## GEOLOGIC CONTROLS ON PRODUCTIVITY

Variability in production patterns can be attributed to several controlling parameters, but specific causes in particular cases are commonly difficult to ascertain. The productivity of a particular Lobo well may be controlled by the volume and internal properties of the reservoir compartment that it is tapping (geologic controls) or by completion and stimulation processes (engineering controls) or by some combination of these two classes of variables. Similarly, the ultimate recovery from a particular Lobo reservoir can depend on geologic attributes, engineering practices, and/or field development strategies.

Once specific controls on Lobo productivity are better understood, strategies can be designed to take advantage of that information. If, for example, a particular depositional facies consistently has the highest porosities and permeabilities and contains a large remaining resource, then geologic techniques can be developed to recognize and map that facies. Geologic models can be constructed that provide a basis for projecting the distribution of the productive facies into undrilled areas. Finding the geologic "key" to the Lobo, however, will not be this simple because of the interrelationship among stratigraphy, structure, and diagenesis. Nevertheless, a better understanding of geologic controls on productivity can help guide research efforts in directions that will yield maximum benefit.

Those geologic attributes having greatest influence on productivity should be targeted for intensive investigation. With the help of Lobo operators, we have identified key geologic uncertainties that present the greatest challenges to successful development (table 1).

Several important benefits can be derived from increasing our understanding of Lobo geology. The most obvious one is geologic targeting of specific zones and locations to increase production. Just as importantly, geologic knowledge can be a valuable tool when designing drilling, completion, and stimulation programs. Different geologic settings require different engineering approaches. Costs can be reduced and stimulation treatments can be made more effective when they are appropriately designed for existing geologic conditions. On a broader scale, a good understanding of the geologic framework of the Lobo can reveal overlooked development and exploration targets, thereby increasing ultimate recovery.

Finally, the Lobo is representative of an important class of gas reservoirs, even though the Lobo displays some of the attributes of this class in their extreme. Geologic methods developed while studying the Lobo will have broad application to other, geologically similar gas plays across the United States.

## NEED FOR COMPREHENSIVE FRAMEWORK STUDY

Site-specific work, such as picking drilling locations and evaluating completion intervals, demands large expenditures of time and technology. Operators individually are focused on this effort and thus lack the time and resources necessary to achieve an adequate understanding of the regional geologic framework, which would reduce uncertainties and guide site-specific work. Knowledge of the regional framework would be critical as a basis for play-wide comparisons to establish controls on productivity and for determining the size and location of the remaining gas resource. Armed with this information, the operators would be able to increase development efficiency and produce a greater percentage of remaining gas in place.

Deployments of advanced gas recovery technologies, hydraulic fracture treatments, and advanced drilling techniques are also hindered by uncertainty concerning the geologic framework. For example, hydraulic fracture treatment design must be tailored to the specific geologic setting in order to achieve both optimal results and accurate interpretation of those results. Furthermore, specific benefits cannot confidently be ascribed to engineering technologies if unforeseen geologic variables are influencing results. The Wilcox Lobo is a prime candidate for advanced, "smart" drilling systems (NRC, 1994), which could seek small targets within the highly faulted Lobo mosaic, potentially revolutionizing resource exploitation by drastically increasing the number of small targets a wellbore—or series of wellbores in a given location—could encounter. Prerequisite to deployment of such a system in the Lobo is a much improved play-wide knowledge of sandstone stratigraphy and fault configurations to provide targets and recognition parameters for the smart drilling system.

Understanding the Lobo geologic framework has implications beyond efficient exploitation of the Lobo gas resource. Experience and technology gained during a study of the Lobo are applicable to a host of geologically similar gas plays across the U.S. Lobo sandstones formed in a marine environment encompassing outer-shelf, slope, and adjacent basin-floor settings. The broad range of conditions that can exist in this environment is controlled mainly by two variables: stratigraphy and structure. In the dynamic outer-shelf/slope environment, a close interplay between depositional and deformational processes produces a spectrum of reservoir types, and the Wilcox Lobo and Paleozoic Canyon Sandstone of South-Central Texas (Laubach and others, 1994) represent near end-members in this spectrum. Canyon sandstones are stratigraphically complex reservoirs in an area having a relatively low degree of deformation, whereas Lobo sandstones apparently display less stratigraphic complexity but are characterized by extreme faulting. Using the Wilcox Lobo and Canyon as representative examples, underlying genetic processes and appropriate advanced geological targeting methods can be determined for an important class of domestic gas reservoirs.

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