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REGIONAL DOMAINS OF THE WILCOX LOBO NATURAL GAS TREND, SOUTH TEXAS

TOPICAL REPORT

(January 1993—October 1994)

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16. Abstract (Limit: 200 words)

The Wilcox Lobo trend is the major low-permeability natural gas producer of the Texas Gulf Coast, having yielded almost 4 Tcf of gas. In recent years Lobo sandstones have accounted for a significant part of domestic tight-gas production: about 13 percent in 1991, the last year for which figures are available. Development activities are growing, marked by rising production rates, producing wells, and active rigs. The Lobo play is recognized to be among the most structurally complex plays in the Gulf Basin. As a result of submarine slumping and widespread normal faulting, sandstone correlation is hampered, nearly completely obscuring play-wide sandstone patterns. Consequently, although success rates are high, in part owing to deployment of 3-D seismic methods, operators surveyed in this study recognize opportunities for further increases in success rates and cost reductions if regional sandstone patterns and other regional geologic variables could be diagnosed. To that end, this report describes regional geologic domains within the Wilcox Lobo play. The setting of the play near the juncture of the Gulf Coast extensional province and the Cordilleran compressional province of Mexico resulted in development of three domains having contrasts in dominant fault trends, sandstone architecture, composition, and diagenesis. The Cotulla domain to the north and east was influenced by a wide, gradually subsiding shelf and has attributes most similar to other parts of the stable Gulf Basin. The Central domain has transitional attributes and an important imprint of salt tectonics. The Burgos Rim domain to the south was affected by a narrow, tectonically modified shelf. It is the least well-explored part of the play. Production characteristics of the three domains differ. Recognition of Lobo domains provides a framework for subdividing the play, documenting and comparing reservoir properties, and predicting sandstone geometry and composition patterns. It is a first step toward establishing regional sandstone and other reservoir attribute patterns that can help guide site-specific work such as interpreting 3-D seismic data and evaluating completion intervals.

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Geologic framework and reservoir properties of the Wilcox Lobo sandstone, identification of regional structural and depositional patterns, regional paleogeographic controls on reservoir attributes, role of salt and basement tectonics in structure of Lobo play

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RESEARCH SUMMARY

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Contractor	Bureau of Economic Geology, The University of Texas at Austin, GRI Contract No. 5082-211-0708, titled "Geologic analysis of primary and secondary tight gas sands objectives"
Principal Investigator	Stephen E. Laubach
Report Period	January 1993—October 1994
Objectives	To increase understanding and utilization of gas resources in the Wilcox Lobo play of South Texas, this report describes regional geologic domains within the play. Recognition of domains provides a framework for subdividing the play, documenting and comparing reservoir properties, and predicting sandstone and reservoir compartment geometry and compositional patterns that have a bearing on reservoir quality.

Technical Perspective

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

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

Results

In order to identify controls on regional sandstone patterns and other regional geologic variables, this report describes geologic domains within the Wilcox Lobo play. The setting of the play near the juncture of the Gulf Coast extensional province and the Cordilleran compressional province of Mexico resulted in development of three domains having contrasts in dominant fault trends, sandstone architecture, composition, and diagenesis. The Cotulla domain to the north and east was influenced by a wide, gradually subsiding shelf and has attributes most similar to other parts of the stable Gulf Basin. The Central domain has transitional attributes and an important imprint of salt tectonics. The Burgos Rim domain to the south was affected by a narrow, tectonically modified shelf. It is the least well-explored part of the play. Production

characteristics of the three domains differ. Recognition of Lobo domains provides a framework for subdividing the play, documenting and comparing reservoir properties, and predicting sandstone geometry and composition patterns. It is a first step toward establishing regional sandstone and other reservoir-attribute patterns that can help guide site-specific work such as interpreting 3-D seismic data and evaluating completion intervals.

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. 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. The regional domain concept leads to specific predictions concerning these attributes that apply to various parts of the Lobo trend.

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

A wide range of geologic and production information from the entire play area and surrounding regions in Texas and Mexico was collected and synthesized. 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 regional stratigraphic correlations and production studies, based on approximately 500 well logs and publicly available production records, 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.

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 new perspective on geological patterns 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 Wilcox Lobo trend is the major low-permeability natural gas producer of the Texas Gulf Coast (Dutton and others, 1993), having yielded more than 4 Tcf of gas. In recent years Lobo sandstones have accounted for a significant part of domestic tight-gas production: about 13 percent in 1991 (fig. 1)—the last year for which figures are available (Hugman and others, 1993). 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 Basin, a view substantiated by our study. This is the result of submarine slumping and widespread, intense faulting that greatly hampers sandstone correlation and nearly completely obscures play-wide sandstone patterns.

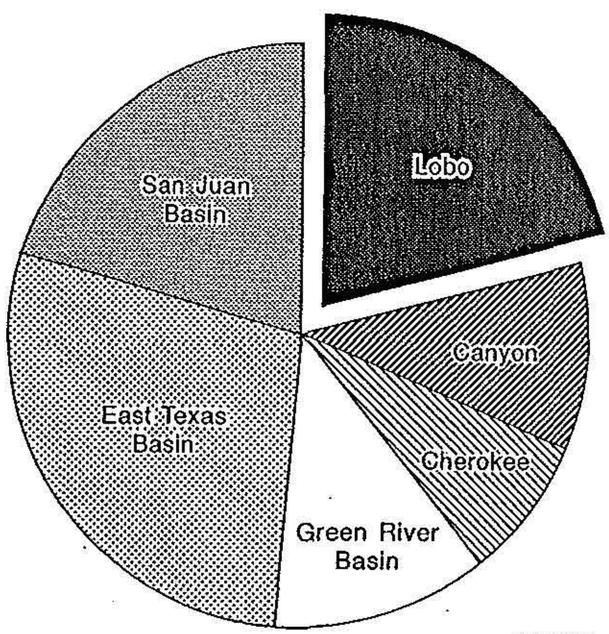

Figure 1. Relative productivities of the major low-permeability sandstones in the western U.S. in terms of 1991 annual production.

Complex geology has nevertheless proven to be an opportunity for those operators who possess accurate geologic information. In such a setting advanced development techniques and completion practices, which allow a progressive movement through time into increasingly challenging reservoirs, have the greatest potential to offset any decline in gas recovery per well. The opportunity for successfully targeting smaller, higher risk reservoirs accounts in part for the increasing use of 3-D seismic data in the Lobo play (Improved Recovery Week, 1994) and points to future potential for technology applications to exploit this emerging gas resource.

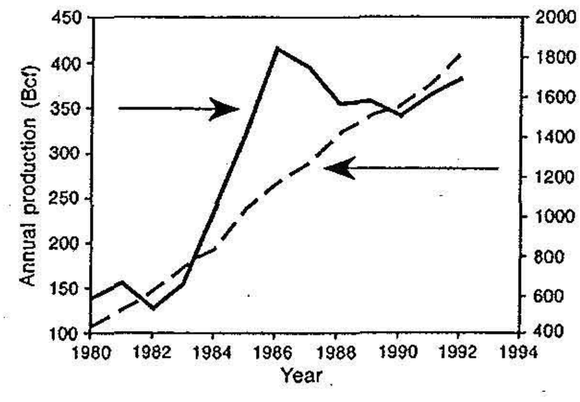

Figure 2. Annual productions and numbers of producing wells for the Lobo play, 1980 to 1993.

This report describes regional geologic domains within the Wilcox Lobo sandstone natural gas play of Webb and Zapata Counties in South Texas. During much of its history, the Lobo was located near the juncture of two major tectonic provinces—the Gulf Coast extensional province, which is dominated by thin-skinned extension, growth faults, and salt tectonics, and the Cordilleran compressional province, characterized by thrusting, folding, basement deformation, and tectonic uplift of highland areas. The Lobo play can be divided into three geographically separate and tectonically distinctive domains that have attributes that reflect the influence of these two provinces. Identification of these Lobo geologic domains provided a framework for subdividing the Lobo play, documenting and comparing reservoir properties, and making reasonable inferences about hard-to-document properties. One of the primary findings of this study is that conventional well-log-based reservoir characterization techniques yield limited useful information about Lobo reservoirs, thus hampering regional sandstone mapping and stratigraphic analysis. Recognition of distinct domains within the Lobo provides predictions about sandstone geometry and composition that can be used to guide regional sandstone mapping and stratigraphic analysis.

Geologic Setting

The Upper Paleocene Wilcox Lobo trend comprises a series of variably geopressured, generally low permeability sandstones in one of the most pervasively 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 thinner 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 includes only the lowermost part of the Wilcox Group in Webb and Zapata Counties, is generally less than 1,200 ft thick, although thicker Lobo intervals are preserved locally near the Rio Grande. Little information on thickness and extent of equivalent sequences in Mexico is available in the U.S. (e.g., Barker and Berggren, 1977; Echanove, 1986). Individual Lobo sandstone reservoirs are generally less than 100 to 200 ft thick and are encased in thicker shales (fig. 4). The Lobo is separated from overlying Eocene Wilcox sandstones by 500 to 1,200 ft of shale; beneath the Lobo is an equally thick Lower Paleocene Midway shale section. Depths to Lobo reservoirs vary widely between 5,000 and 14,000 ft.

The Lobo interval comprises seven distinctive sandstone zones, termed, in descending order, the Walker and Lobo 1 through 6. These are overlain by an irregularly interbedded sandstone/shale section called the "stray" (fig. 4). Several Lobo zones extend throughout the play area, whereas others are more

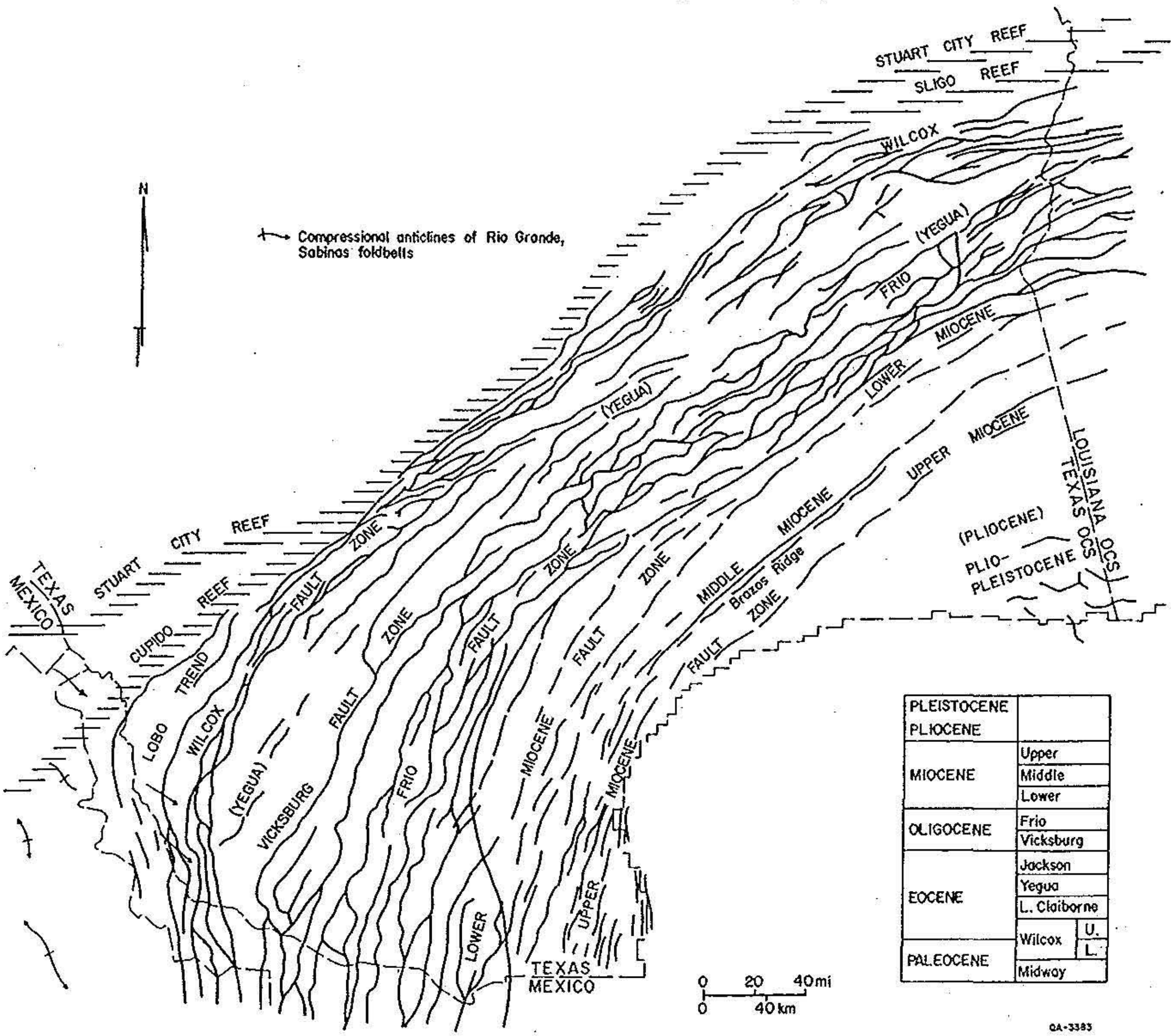

Figure 3. Regional fault zones and producing trends for the Texas Gulf Coast Tertiary Basin. From Ewing (1986).

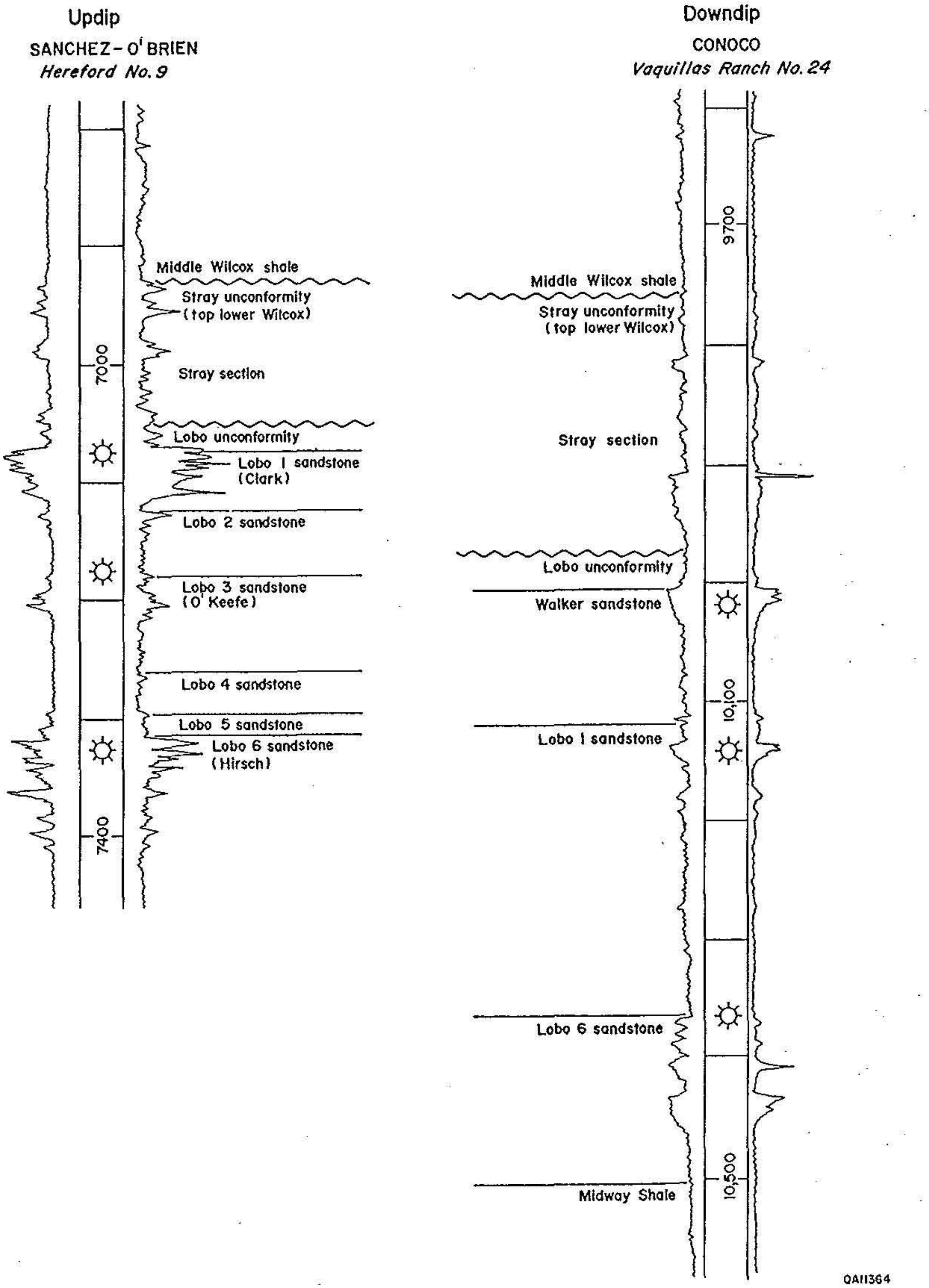

Figure 4. Typical logs from the lower Wilcox Lobo trend showing productive sandstones and unconformities. Modified from Long (1986). Well locations shown in figure 5.

local (fig. 5). Extensive postdepositional deformation and erosion have profoundly modified Lobo strata (fig. 6). Shortly after deposition, the main Lobo zones were first subjected to intensive faulting, then to erosional truncation to form the Lobo unconformity. The stray section was then deposited on the unconformity and was subjected to a second phase of faulting and erosion. Additional episodes 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, disrupting the lateral continuity of what were initially sandstone sheets.

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 based upon biostratigraphic analyses reported by Lobo operators and confirmed by similar analyses performed during our study. Previous environmental interpretations have been based primarily upon core descriptions from local areas. Our work suggests that several different kinds of depositional systems were active across the Lobo region.

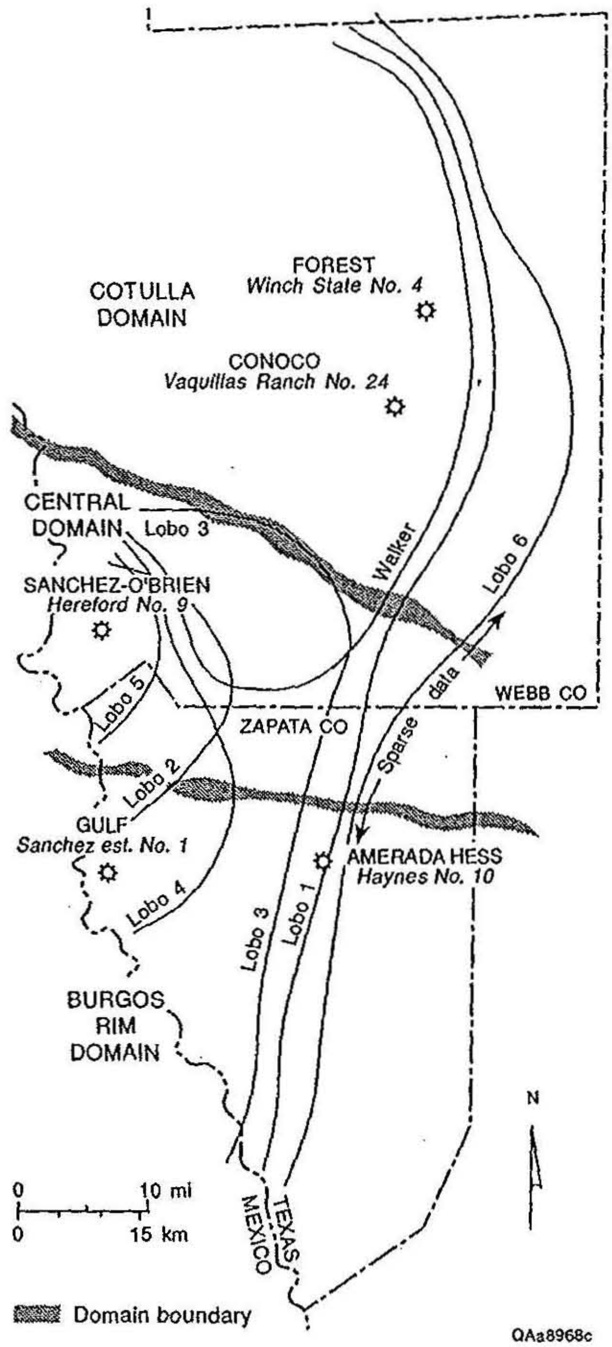

Figure 5. Lateral extents of Lobo productive sandstones, locations of typical logs (fig. 4), cored wells used in this study, and domain boundaries (stippled). Boundaries are gradational. Sandstone distribution modified from Long (1986).

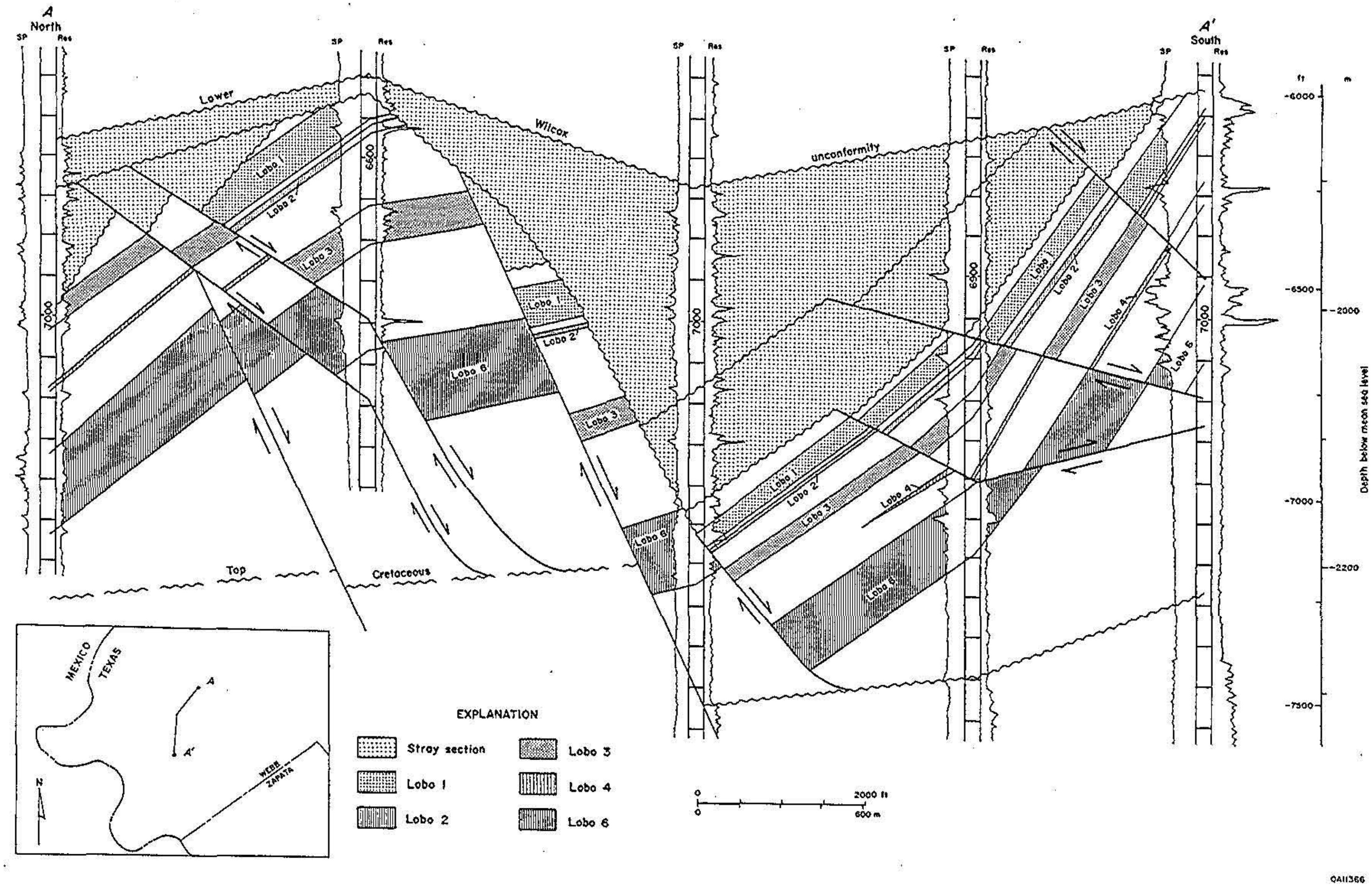

Figure 6. North-south cross section of Laredo (Lobo) field, Webb County, Texas, showing complex configuration of faults and unconformities that compartmentalize Lobo reservoirs in Central domain. From Railroad Commission of Texas (1977).

Lobo Geologic Domains

The physical attributes of Lobo reservoirs can be related back ultimately to broad regional tectonic and paleogeographic settings. The Lobo play occupies a unique position at the boundary between the Gulf of Mexico Basin and the Cordilleran fold–thrust belt of northeastern Mexico (fig. 7). The northwestern Gulf Basin is a northeast-striking, divergent continental margin characterized by regional subsidence and thin-skinned gravity-driven extension, whereas the late Mesozoic–Cenozoic Cordilleran belt in Mexico comprises west- and northwest-trending folds (fig. 3) and primarily northeast-directed thrusts. The northeast part of the Lobo play falls within the Gulf Basin realm, the southwest part of the play (including its extension into Mexico) comes within the influence of the fold–thrust belt, and the middle of the play forms a broad transition zone.

On the basis of these key differences in tectonic setting and on differences in structural styles and fault orientations, we identified three distinct geologic domains within the Lobo trend: the Cotulla, Central, and Burgos Rim domains (fig. 8). The Cotulla domain is named for the Cotulla barrier-bar system of Fisher and McGowen (1967), which influences attributes of this domain; the Burgos Rim domain is named for its position on the flank of Burgos Basin, Mexico; and the Central domain represents the transition between the two domains. Within each Lobo domain, distinctive tectonics controlled paleogeographic setting, which in turn exerted varying levels of influence on all geologic factors affecting reservoir properties: (1) sediment source areas, transport directions, and composition, (2) depositional and erosional patterns, (3) sand-body geometry and orientation, (4) fault geometries and reservoir compartmentalization, (5) natural fracture attributes, and (6) sandstone diagenesis and, probably, fluid dynamics. The defining attributes of the Lobo domains are summarized in table 1.

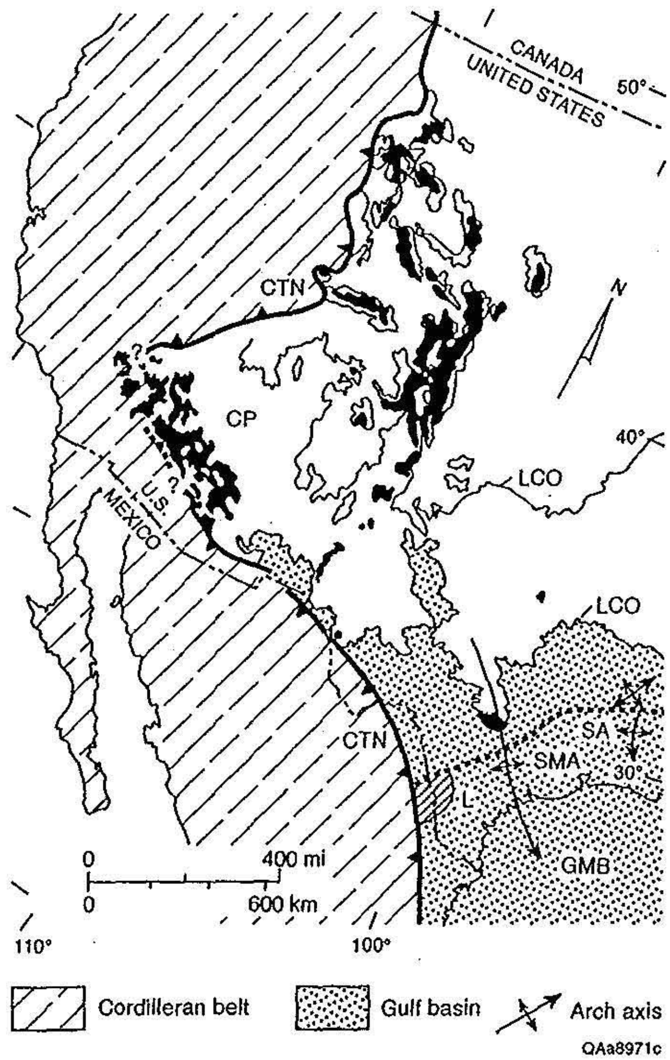

Figure 7. Tectonic setting of the Wilcox Lobo play. Play is near the juncture of the Cordilleran belt of contraction in Mexico and the Gulf Basin extensional province. CTS, southern segment of Cordilleran thrust belt (Sierra Madre Oriental); CTN, northern segment of thrust belt. Deformation style varies considerably along length of belt. Black areas indicate uplifts with exposed crystalline basement rocks. Broken line in Gulf of Mexico marks approximate location of transition from thick to thin transitional extended crust. SMA, San Marcos Arch and SA, Sabine Arch are postulated to be in part foreland uplifts related to Cordilleran tectonism. L, Lobo play.

Cotulla Domain

Tectonic Setting

The Cotulla domain, the northeasternmost of the three Lobo domains (fig. 8), is dominated by Gulf Coast extensional tectonics. Closely spaced (ca. 1,500-ft) northeast-striking, strike-aligned normal faults segment Lobo reservoirs and impart a northeasterly elongation to productive areas. The updip boundary of the Cotulla domain (and of Lobo production) coincides with the underlying Cretaceous shelf edge (Sligo or Cupido Reef trend, fig. 3). The Cotulla domain is bounded downdip (southeast) by the southeast-facing Upper Wilcox growth fault zone. The northeastern boundary is delineated by stratigraphic pinch-outs of Lobo sandstones (fig. 5), although the precise locations of these pinch-outs are not well documented. To the southwest the Cotulla domain grades into the Central domain across a broad area where structural trends become progressively more north-oriented (fig. 8).

Lobo extensional tectonics initiated basinward of the relict Cretaceous shelf edge. Lobo depositional systems prograded across this rigid carbonate margin and out onto plastic slope mudstones of Upper Cretaceous and Paleocene Midway Group formations. Loading-induced basinward sliding and spreading of these plastic shales—and locally of deep-seated Jurassic salt—caused tilting, slumping, and faulting in overlying Lobo shelf sandstones. Following the initial episode of gravity-driven extensional deformation, Lobo sandstones were subjected to subaerial or subaqueous erosion; truncation was apparently greatest on high-standing fault blocks. One or more additional episodes of faulting followed and alternated with episodes of deposition and erosion.

Following formation of the Lobo, thick Middle Wilcox marine shales were deposited on the subsiding Lobo platform. A major growth fault system formed along the downdip margin of the Lobo platform when large sand-rich Upper Wilcox deltas prograded across the Middle Wilcox shales (Bebout and others, 1982; Ewing, 1986). Downward extensions of some Upper Wilcox growth faults further segment Lobo sandstones.

Paleogeography

During Lobo deposition, the paleogeographic setting of the Cotulla domain included a broad continental shelf flanked updip by an equally broad, low-lying coastal plain and downdip by an unstable continental slope. Lobo shoreface and shelf depositional systems in the Cotulla domain probably received sediment from two sources: along-shelf transport from large Lower Wilcox delta systems to the northeast (Fisher and McGowen, 1967) and basinward transport from smaller fluvial-deltaic systems in Mexico (Echanove, 1987) (figs. 9 and 10). Within the Cotulla domain, however, preserved sandstones are predominantly marine shoreface and shelf facies, such as barrier bars, offshore bars, and tidal inlets.

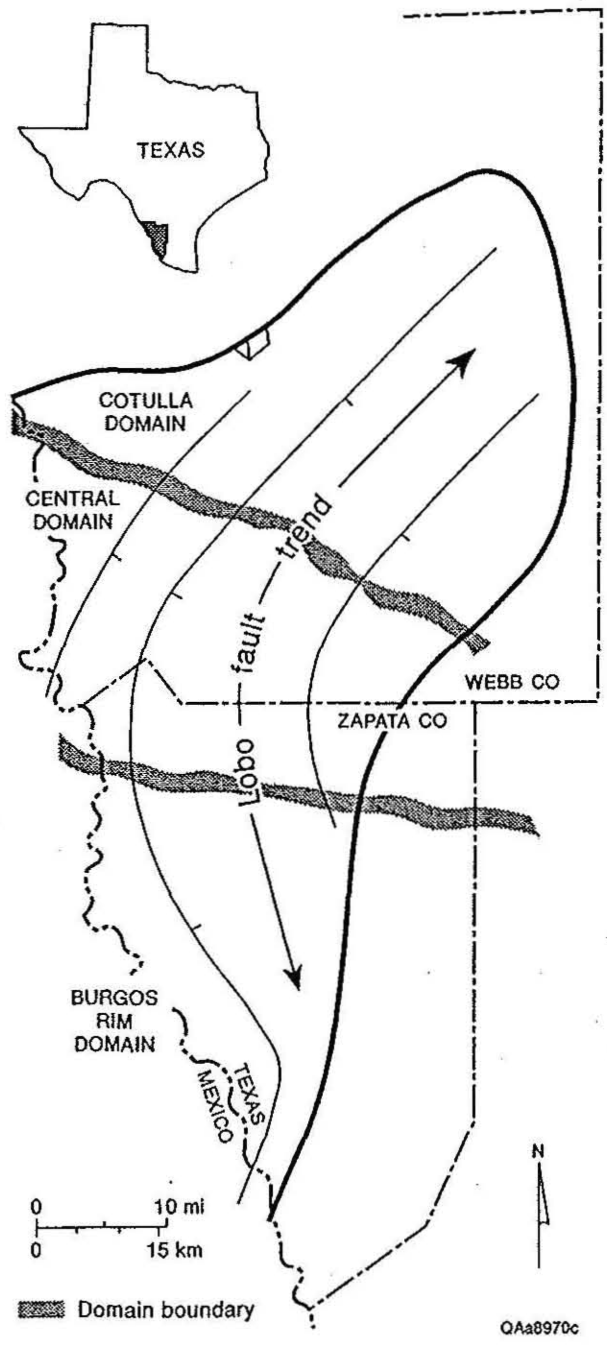

Figure 8. Location of Wilcox Lobo domain boundaries. Generalized trends of dominant faults are also shown. Domain boundaries are gradational. Criteria for identification of domain boundaries are described in the text.

Table 1. Geologic attributes of Wilcox Lobo domains.

	Sand-body geometry	Sandstone composition	Sandstone provenance	Fault trends	Fault style	Salt-tectonic influence	Fluid attributes
Cotulla	ENE and NE; shore-parallel; some influence of K reef trends & Cotulla barrier-bar system	Feldspathic litharenites to sublitharenites; carbonate & shell material present; iron-bearing chlorite; kaolinite	Shore-parallel transport from Rockdale fluvial-deltaic system; biotite from a cratonic igneous source	NE to ENE; secondary NW faults; orthogonal NE and NW joints, fractures; mostly down to basin	Normal faults, down to basin, wider spacing; open joints, fractures common	In zone of isolated salt structures; salt variably present and probably thin	Lobo interval generally above top of geopressure; normal thermal gradients
Central	Dominantly NE; shore-parallel, with secondary NW influence of paleo-Rio Salado fluvial system; mid- to outer shelf	Feldspathic litharenites; carbonates sparse; metamorphic rock fragments and metamorphic quartz	Principally from NW—paleo-Rio Salado drainage; also erosion from tilted fault blocks in gravity slide	NE to N with well-developed NW set	Normal faults; the largest are down to basin; small NW grabens, half-grabens common; gravity-slide blocks with variable tilt	In zone of salt anticlines and domes; Lobo gas production at Pescadito; evaporites probably involved in gravity slide	Lobo sands variably geopressured; normal thermal gradient
Burgos Rim	N to NW strike-elongate system; some influence of older NW ridges; greatly expanded Lobo section; deeper water deposition; some margin-parallel outer-shelf sand bodies	Most variable: subarkose/lithic arkose/feldspathic litharenite/sublitharenite; anhydrite more abundant; volcanic rock fragments; illite/smectite (volcanic-derived clays); much chert; muscovite, glauconite	Primarily from W; paleo-Rio Sabinas drainage	NNW with secondary ENE cross faults	Normal, down-to-basin faults and E to ENE grabens	Evaporites at great depth; appear to exert little influence at Lobo level	Lobo is generally geopressured and thermal gradient elevated

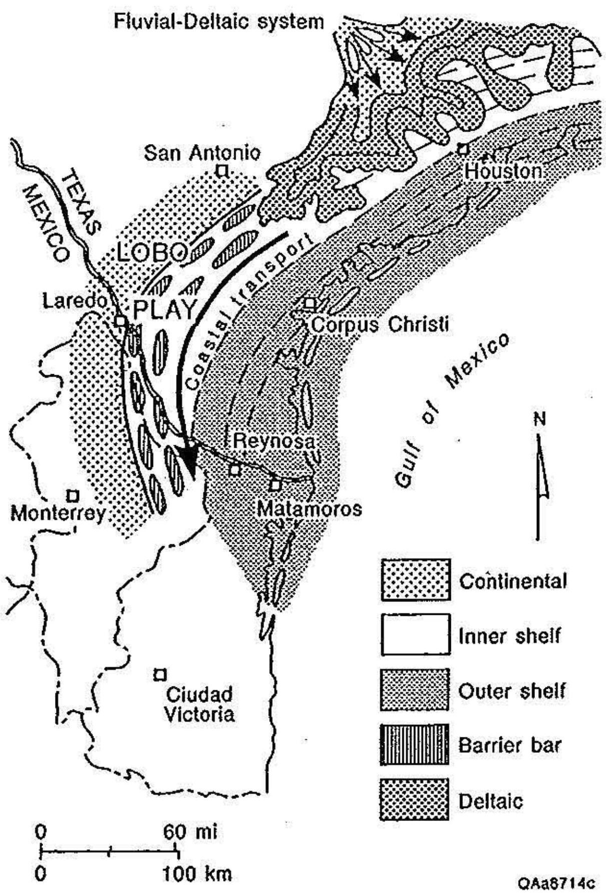

Figure 9. Cotulla barrier bar and shelf system, a key influence in the Cotulla domain. Cotulla barrier bar and shelf system was interpreted by Echanove (1986) to extend southward along the Burgos Basin margin.

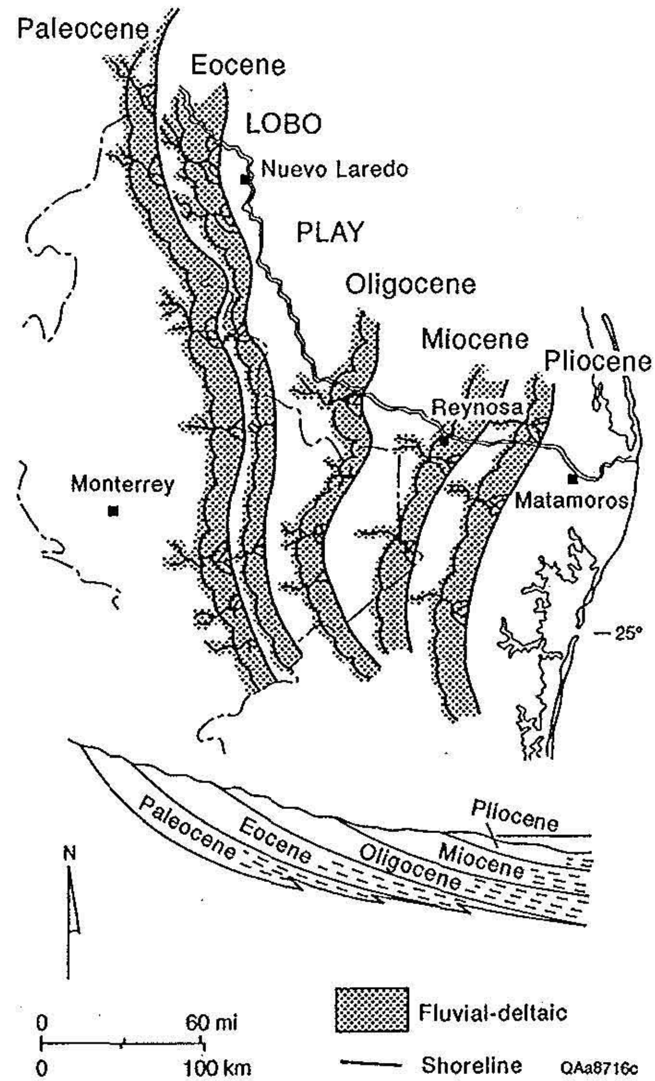

Figure 10. Tertiary fluvial-deltaic systems of the Texas–Mexico border region. Migration of such systems through time influenced the evolution of Wilcox Lobo domains. Tertiary paleogeography of Rio Grande Embayment and basinward progradation of fluvial-deltaic and littoral facies with time (Echanove, 1986).

Reservoir Geometries

Although the Lobo sandstone zones are broadly continuous across the play area (fig. 5), internal stratigraphically controlled high-permeability compartments and low-permeability flow barriers in the Cotulla domain are mainly strike-aligned (northeast). Externally, reservoirs are bounded mainly by fault planes and surfaces of erosion. Since the major faults trend dominantly northeast, fault-bounded compartments are elongated in that direction, paralleling the stratigraphic grain. Erosional truncation was probably more irregular, creating reservoir compartments of varying size and shape. Thus, Cotulla domain reservoirs can be expected to display a range of shapes and orientations, but the dominant direction of elongation should be northeast.

Biostratigraphy

In order to assess variability among Lobo sands 1 through 6 in the Cotulla domain, we conducted thin-section, palynologic, and foraminiferal biostratigraphic analyses of the Lobo interval cored in the Forest Oil Russell Winch State No. 4 well, Mujeres Creek field, Webb County (figs. 5 and 11). Although biostratigraphic zonations are well established for Lobo-equivalent strata along the central and eastern Gulf of Mexico rim, data are sparse for the Rio Grande Embayment. Palynologic and foraminiferal analyses may be useful for sandstone identification and correlation within this structurally complex region.

Palynomorphs (fair to poor preservation) are yellowish-brown to brownish-yellow, indicating 3.0 to 4.0 on the Staplin color scale of organic maturity. Both pollen and foraminifera (good to excellent preservation) recovered from this core indicate deposition of the sands in a middle to outer shelf environment. The entire package of Lobo sands sampled is Upper Paleocene (zone P4) but below the Paleocene–Eocene boundary. Our analyses showed that palynologic and foraminiferal assemblages display some differences among the different Lobo sandstone zones and therefore are potential correlation tools. Analyses of samples from other wells in the trend would help determine the full extent of their usefulness.

Sandstone Composition

Seven Wilcox Lobo sandstone samples from the Forest Winch State No. 4 well were examined for texture, composition, and diagenetic history by means of standard thin-section petrography. An additional goal was to compare findings to those of published petrographic 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 visibly 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 the Cotulla domain are very fine grained. Samples range from poorly to moderately well sorted; most clean sandstones are moderately sorted. Sand grains are angular to rounded. The sandstones examined are mineralogically immature, and most samples are classified as feldspathic litharenites according to the sandstone classification of Folk (1974), although considerable range in composition is evident (fig. 12). 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 10 to 15.5 percent of whole-rock volume (table 2). 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. Rare 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).

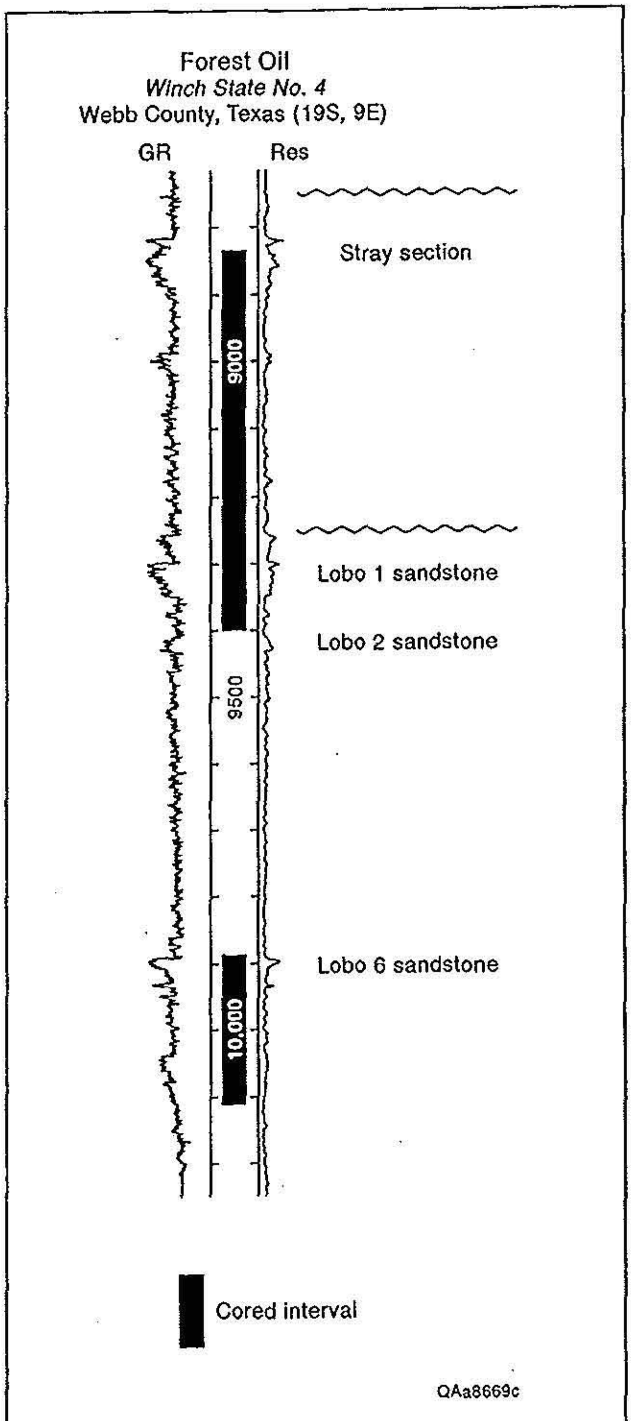

Figure 11. Forest Oil Winch State No. 4, Webb County, Texas. Core from this well illustrates Cotulla domain attributes.

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 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.

Composition of Lobo sandstones from the Forest Winch State No. 4 well is similar to that of other Cotulla domain sandstones. Data compiled from our measurements and unpublished industry sources suggest that sandstone composition varies between Lobo sandstones within the Cotulla domain (fig. 13), but sandstones are dominantly feldspathic litharenites, grading into sublitharenites and litharenites. Sandstones contain a large percentage of quartz and sedimentary lithic fragments, and shell fragments and other calcareous debris are prominent minor constituents. Abundant carbonate materials, in the form of both shell fragments and cements, are typical constituents of sandstone in this domain.

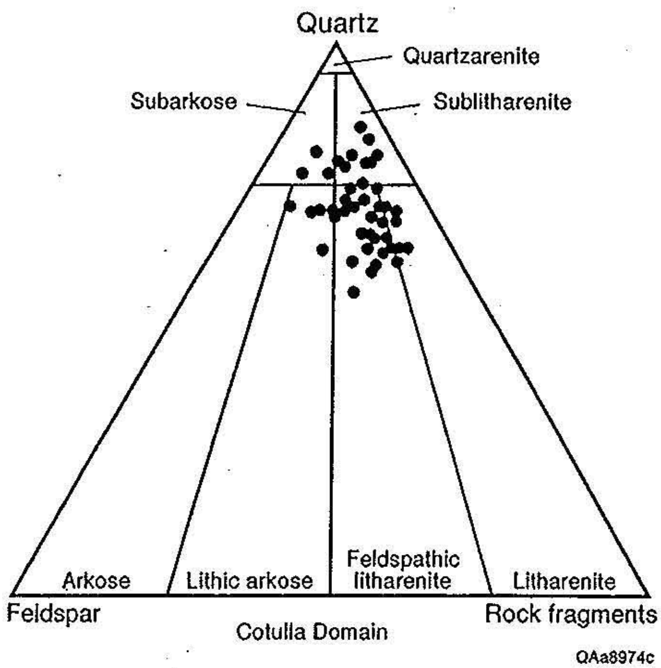

Figure 12. Composition of sandstones in the Cotulla domain. Data from Forest Oil Winch State No. 4 and various unpublished industry sources.

Table 2. Petrographic analyses of Wilcox Lobo sandstones from the Forest Oil Winch State No. 4 well, Webb County, Texas. Values given in percent of whole-rock volume.

Constituent	Range (%)	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

Diagenesis

As manifested in the Forest Oil Russell Winch State No. 4 core, the primary diagenetic events in the burial history of Lobo sandstones in the Cotulla domain 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.

Iron-bearing chlorite and kaolinite are clay minerals present in Cotulla domain sandstones. The whole-rock volume of chlorite cement varies from 0 to 7.5 percent (table 2). Chlorite, the first cement to form in our Lobo sandstone samples, 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 2). Quartz cementation postdated formation of chlorite rims.

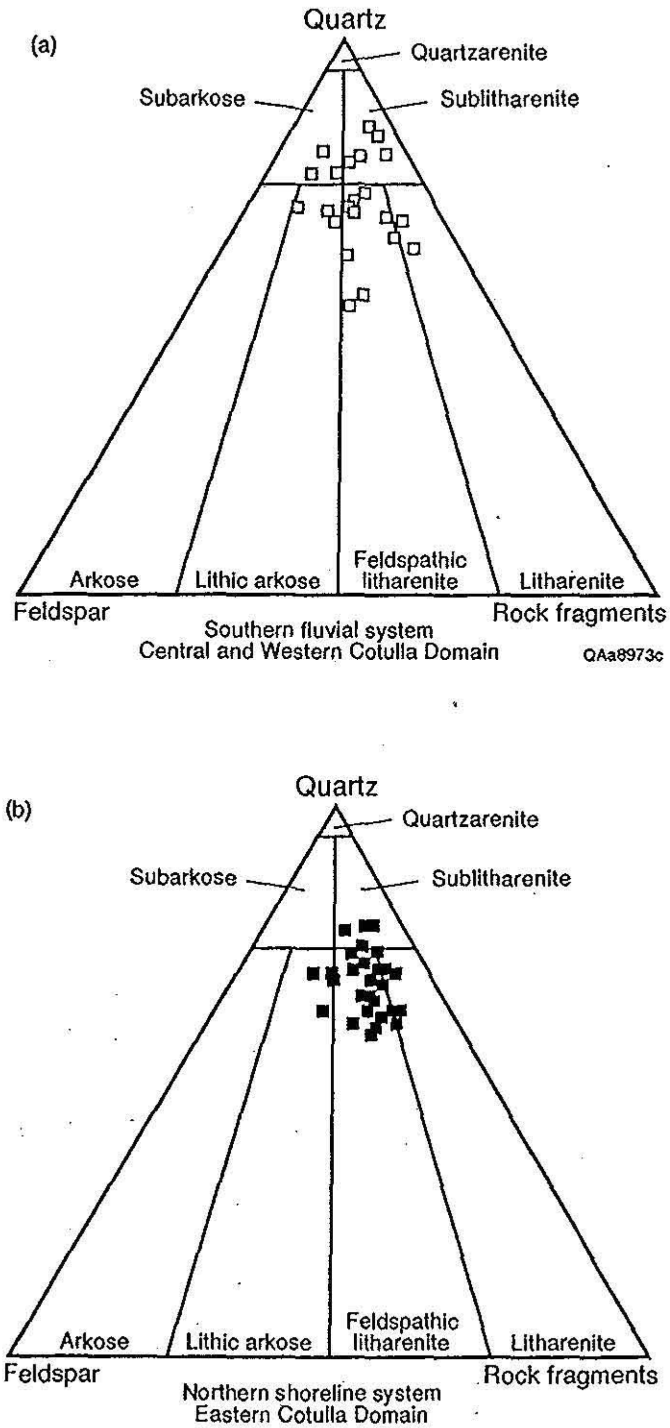

Figure 13. Comparison of sandstone composition in the Central and western Cotulla domain with those of eastern Cotulla domain. Data from Forest Oil Winch State No. 4 and various unpublished industry sources. (a) Central domain and western Cotulla domain, showing influence of the southern fluvial system. (b) Eastern Cotulla domain, showing influence of northern shoreline system. QFR (quartz:feldspar:rock fragments) ternary diagram illustrating detrital components of Wilcox Lobo sandstone samples from the Forest Oil Corporation Winch-State No. 4 core.

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. These observations suggest that quartz cement in at least part of the Lobo play is synkinematic with respect to fracture opening. In other tight gas formations, quartz-filled microfractures in synkinematic quartz cements are useful guides to macroscopic fracture patterns (Laubach, 1989).

Ankerite, the second most abundant cement in our Lobo sandstone samples, has a range of whole-rock volume from 3.0 to 10.5 percent (table 2). Ferroan calcite (fig. 16), another carbonate cement, occurs in only one of the samples, where it composes as much as 12.5 percent of the sample. 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

Porosity observed in thin section is almost all secondary. Core measurements indicate that porosity values vary from 0 to 14.5 percent (table 3). 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,

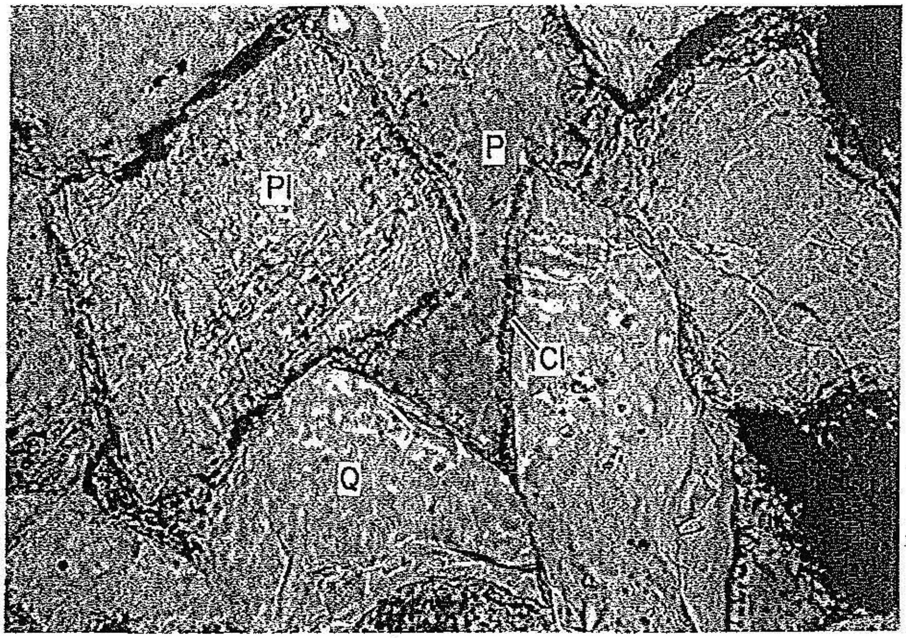

Figure 14. Photomicrograph showing chlorite grain-rimming cement (Cl), primary porosity (P), and quartz (Q) and plagioclase (Pl) framework grains. From Forest Oil Winch State No. 4 (Lobo 1, 8,869 ft). Horizontal dimension of photograph is 0.5 mm.

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

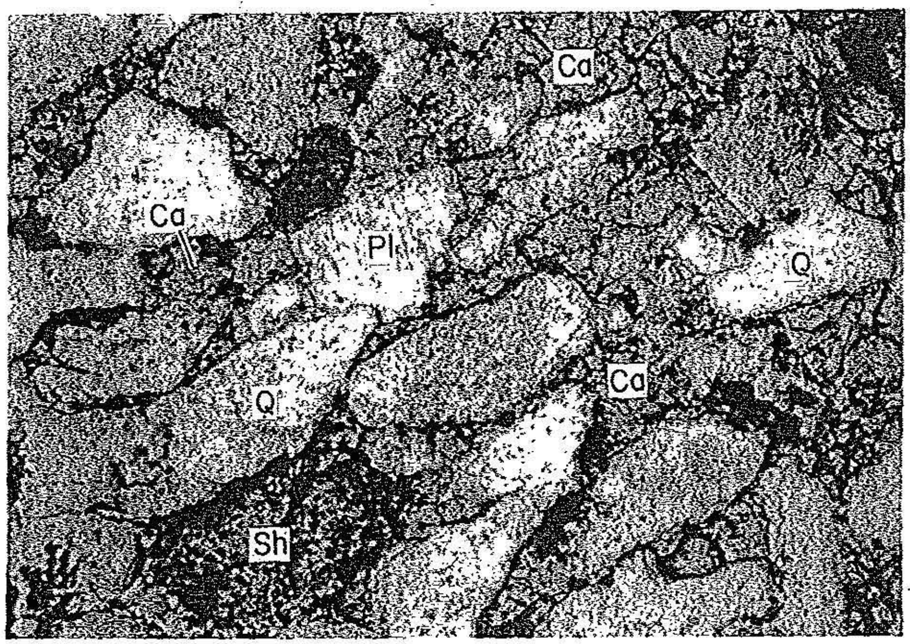

Figure 16. Photomicrograph of abundant, porosity-occluding ferroan calcite cement (Ca) found in some zones of Lobo reservoirs. Framework grains include quartz (Q), plagioclase (Pl), and shale rock fragment (Sh). From Forest Oil Winch State No. 4 (Lobo 2, 9,327 ft). Horizontal dimension of photograph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

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 gas permeability measured at net overburden 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). Porosity and permeability measurements from selected industry wells are summarized in figure 18.

Findings of our core study generally agree with those of Alexander and others (1985). Some 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. If depth of burial is key to feldspar dissolution, it is possible that feldspar content varies across domains since each domain encompasses a range of burial depths. Alexander and others' (1985) shallower core samples from the Cotulla domain 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). Another factor that is not accounted for in domain analysis of the Lobo is the effect on diagenesis that may result from proximity to faults and the fluid-circulation systems associated with them (fig. 19).

Table 3. Porosity and permeability of selected Cotulla and Central domain sandstones.

	Cotulla Lobo 3 porosity	Cotulla Lobo 3 permeability	Cotulla Lobo 1 porosity	Cotulla Lobo 1 permeability	Cotulla Lobo 6 porosity	Cotulla Lobo 6 permeability	Central Lobo 1 porosity	Central Lobo 1 permeability	Central Lobo 6 porosity	Central Lobo 6 permeability
Minimum	5.7	0.01	6.2	0.01	1.8	0.0	8	0.02	8.5	0.0
Maximum	24.7	1.9	31.8	67	28.5	64.5	24	51	19.8	0.6
Number of measurements	82	82	132	131	774	753	20	17	9	9
Mean	15	0.3	18.5	9.8	13.6	1.1	19.0	27.4	16.2	0.2
Median	14	0.1	19.7	1.6	13.6	0.06	22.3	29.7	16.4	0.1
RMS	15	0.6	19.2	18.5	14.3	4.9	19.8	32.4	16.5	0.3
Std. Deviation	5	0.5	5.3	15.7	4.4	4.7	5.6	17.9	3.2	0.3
Variance	26	0.24	28.2	249.3	19.3	23	31.7	322.0	10.0	0.1
Std. Error	0.6	0.05	0.4	1.2	0.2	0.2	1.2	4.3	1.0	0.1
Skewness	0.2	1.9	–0.5	1.8	0.08	8.5	–0.98	–0.3	–1.6	1.0
Kurtosis	–1.0	2.6	–0.4	2.6	–0.4	88.1	–0.7	–1.2	2.1	–0.5

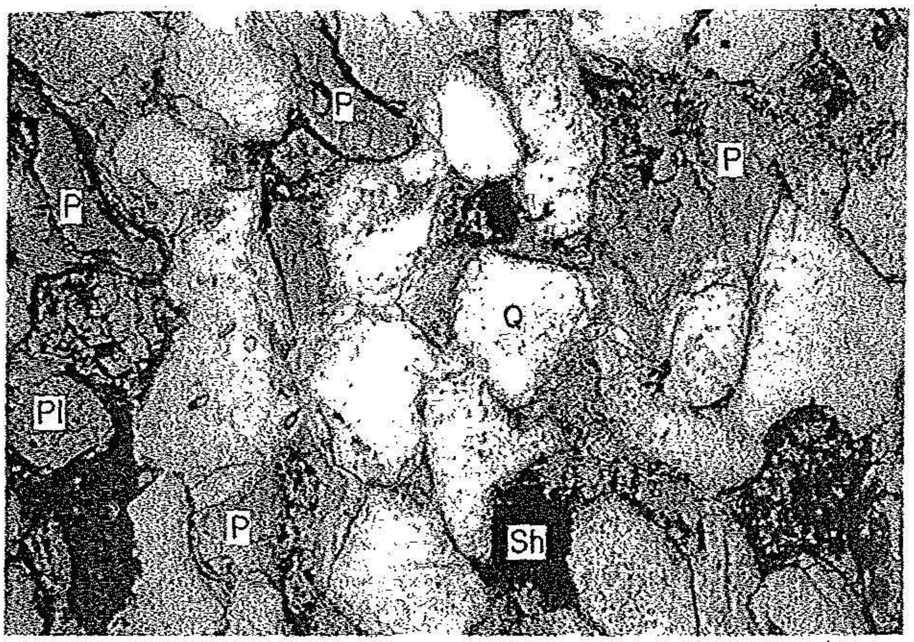

Figure 17. Photomicrograph of abundant secondary porosity (P) produced by dissolution of clay-rich rock fragments. Framework grains include quartz (Q), plagioclase (Pl), and shale rock fragment (Sh). From Forest Oil Winch State No. 4 (Lobo 2, 9,330 ft). Horizontal dimension of photo is 1.3 mm.

Fractures and Salt Structures

Fractures are evident in unpublished industry core photographs from Cotulla domain wells and in core obtained for this study. The cores are not oriented, and the sample of fractures is too limited to draw any general conclusions about fractures in the Cotulla domain. Many of the fractures are subvertical opening-mode fractures, whereas others appear to be either tectonic or soft-sediment normal faults. The Lobo, by virtue of widespread mapped faults on a range of scales, is agreed to be a reservoir that contains fractures, but the possible role these features may play in enhancing deliverability or causing permeability anisotropy is unknown.

Outcrop observations provide some suggestion of fracture trends in the Cotulla domain. Open joints and fractures are easily observable on aerial photographs and satellite images although less easily seen at ground-level in the field; the joints form orthogonal north-easterly and northwesterly sets (fig. 20).

The Cotulla domain is in a zone of isolated salt structures. Most of these structures are low-relief salt-cored anticlines (structural ridges). Salt is discontinuous and probably thin. Current salt thickness and salt thickness at the inception of Lobo extension are unknown. Physical models of salt deformation in the Gulf Basin and elsewhere (e.g., Jackson and others, 1994) provide a basis for predicting locations and styles of salt-involved structures in this domain.

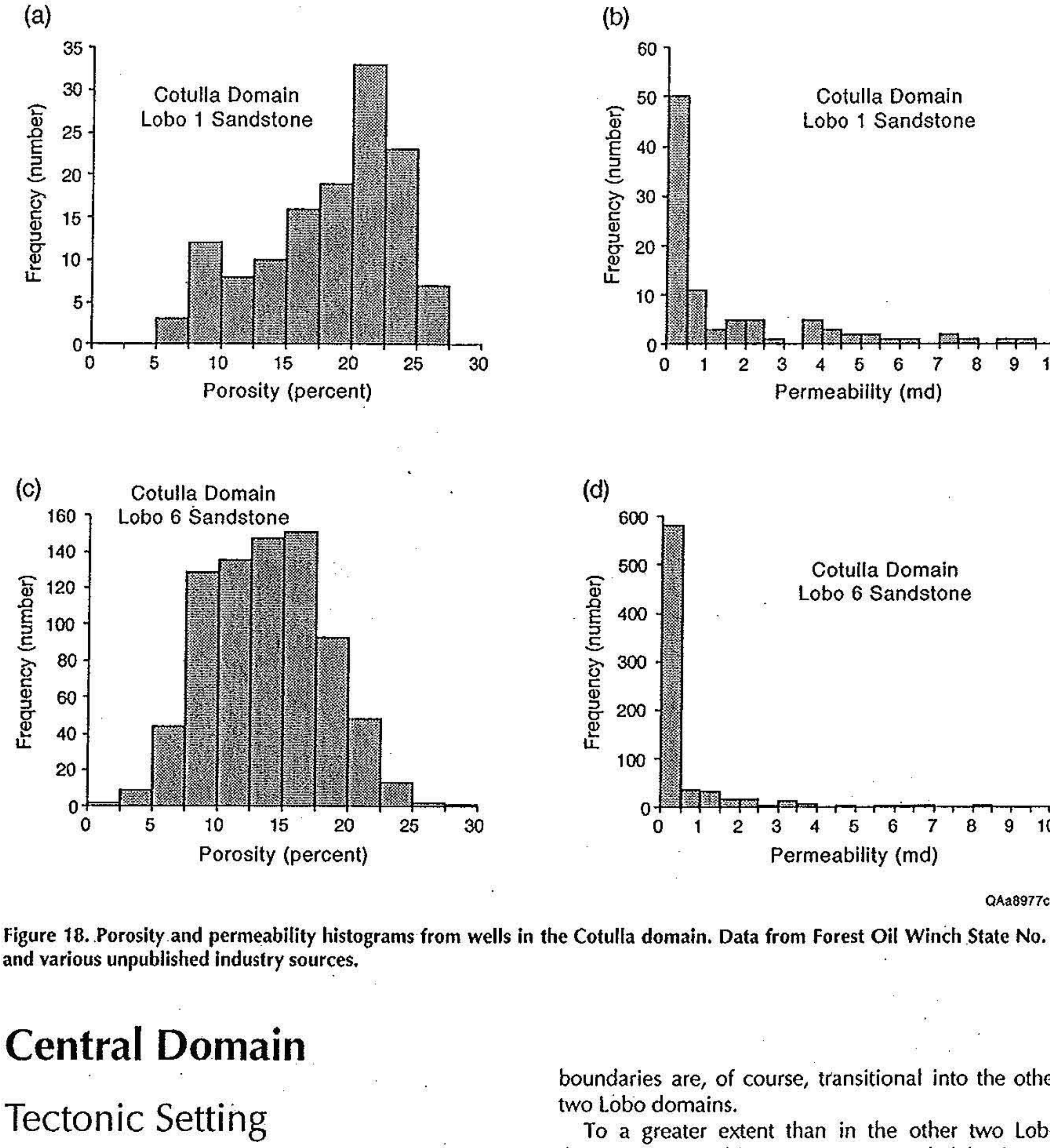

Figure 18. Porosity and permeability histograms from wells in the Cotulla domain. Data from Forest Oil Winch State No. 4 and various unpublished industry sources.

Central Domain

Tectonic Setting

The Central domain is a broad transition zone in which the northeast-trending structures of the Cotulla domain intersect the north- to northwest-trending structures of the Burgos Rim domain (fig. 8). Consequently, faults in the Central domain display a wide range of strikes; intersecting northeast- and northwest-striking faults are common. As in the Cotulla domain, a relict Cretaceous shelf-margin reef trend forms the updip boundary, although in the Central domain that boundary lies in Mexico (fig. 3). The downdip boundary is the Upper Wilcox growth fault trend, and the lateral boundaries are, of course, transitional into the other two Lobo domains.

To a greater extent than in the other two Lobo domains, gravity-driven tectonics pervaded the Central domain, producing the characteristic multiple episodes of deposition, extensional deformation, and erosion. Distinguishing tectonic features of the Central domain include northward-decreasing compressional deformation and gradual south-to-north change in structural strike (fig. 8). Subtle southeast-plunging folds extend into the south part of the Central domain but diminish toward the north and east. Major extensional fault zones strike north to northwest in the south but curve through a broad concave-basinward arch to strike northeast in the north.

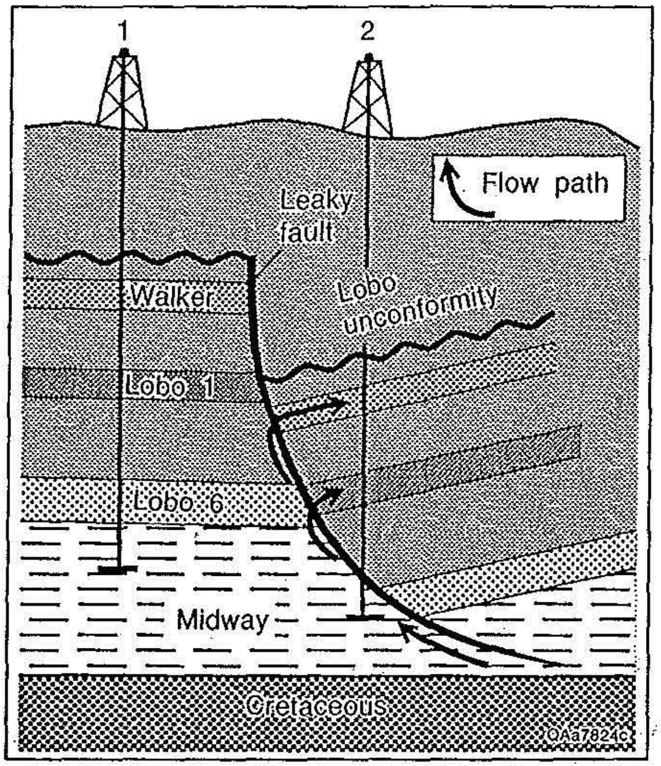

Figure 19. Schematic cross section illustrating upward migration of formation waters along a leaky fault and channeling of waters into Wilcox Lobo reservoir zones. This process may be responsible for the considerable variation in diagenetic characteristics across the trend.

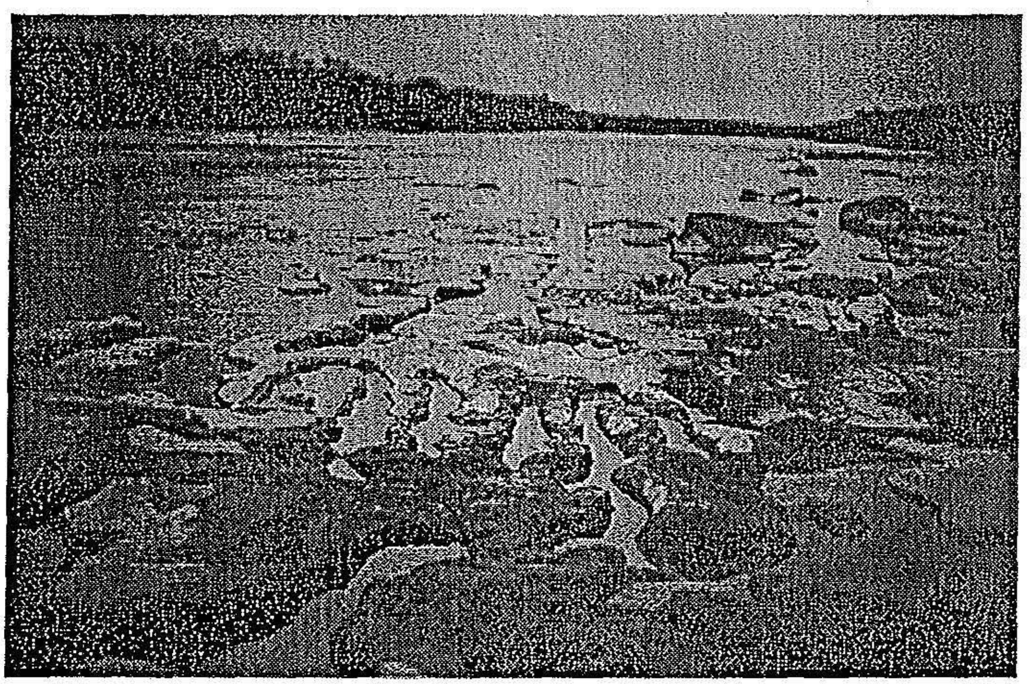

Figure 20. Joint systems in Upper Cretaceous Escondido sandstone, Central domain. Outcrop in Rio Grande near El Indio, Webb County, Texas, shows surface fracture patterns in this domain. View to southeast (down river) along principal northwest-trending joints; a well-developed northeast set crosscuts the northwest joints.

Paleogeography

Lying in the zone of convergence of two differently oriented tectonic regimes, the paleogeography of the Central domain is complex and characterized by abruptly varying depositional and structural elements. The widths of the Lobo shelf and coastal plain in the Central domain are intermediate between those in the Burgos Rim and Cotulla domains. Northward-extending Cordilleran highlands in Mexico (fig. 7) formed the updip hinterlands and sediment source areas for the Central domain, which are, therefore, similar to those of the Burgos Rim. Although sediment transport directions were dominantly eastward, along-shelf transport from the northeast was probably a secondary source of sediment for the north part of the Central domain. Even sand from the western source areas was probably at least partly reworked along strike on the Lobo shelf (fig. 21).

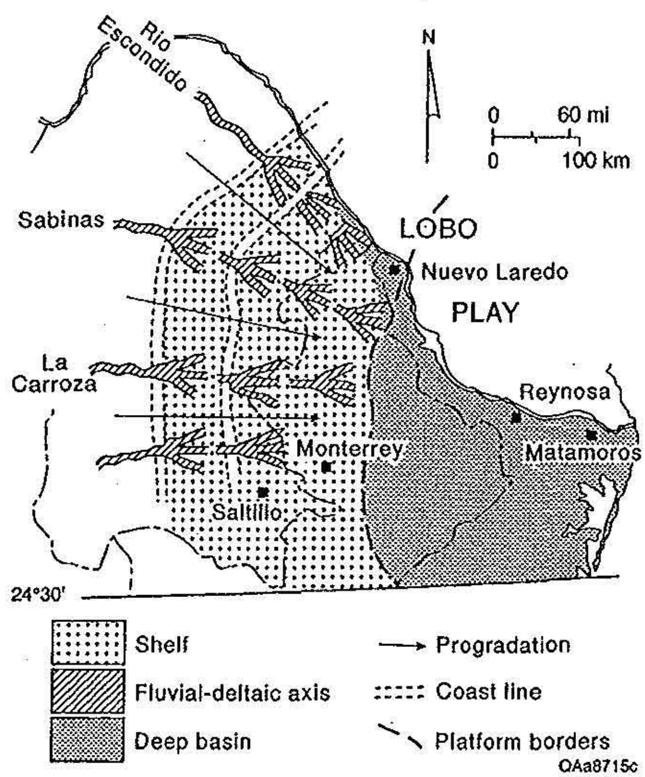

Figure 21. Fluvial influences on the Central and Burgos Rim domains. Latest Cretaceous paleogeography and eastward-prograding fluvial-deltaic systems. Progradation reflects onset of Laramide deformation and uplift farther west at this time. We infer that the Rio Escondido, Sabinas and La Carroza systems were also significant in transporting Lobo sands during the late Paleocene. From Echanove (1988).

Reservoir Geometries

Because of the curving shape of the Central domain shelf, strike-aligned sand-body elongations range broadly from northeast to northwest, and dip-oriented sand-body elongations range from southeast to east. Internal stratigraphically controlled permeability compartments must also display a broad range of elongations. There should be, however, a systematic change in dominant elongation direction in the Central domain, from similar to dominant elongation directions in the Cotulla domain in the north to similar to those in the Burgos Rim domain in the south. Fault- and unconformity-bounded reservoir compartments likely also have systematic changes in orientation. Thus, location within the Central domain with respect to proximity to either of the other two domains can provide important information concerning expected reservoir geometry.

Composition and Rock Properties

Only limited data were available on rock composition and properties for sandstones in the Central domain (figs. 22 and 23). Generally, sandstones

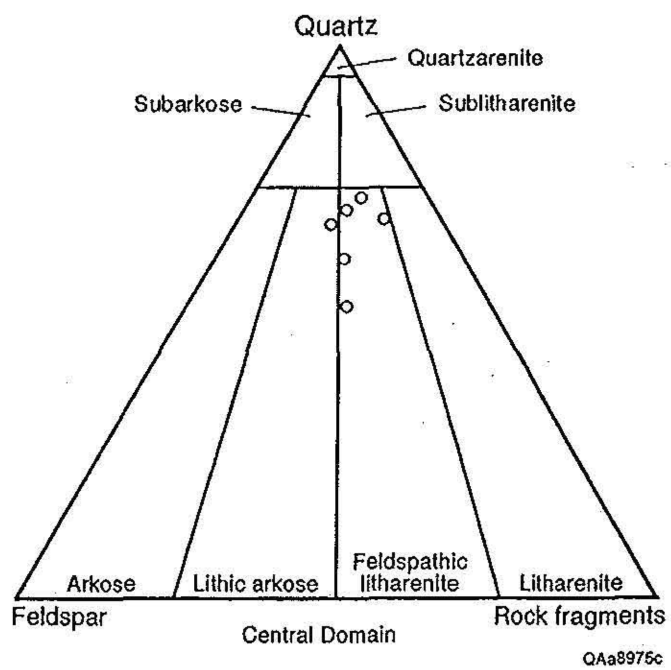

Figure 22. Sandstone composition from several wells, Central domain. Enrichment in feldspar and rock fragments is evident compared to that in eastern Cotulla domain, yet QFR diagrams may not be highly sensitive to shifts in source areas in these domains.

are feldspathic litharenites. Although these compositions are similar to those of the Cotulla domain, slight differences are evident in average compositions. The statistical significance of these differences could not be evaluated with the limited data available. An indication that these variations may reflect differences in source areas is the change in relative abundance of minor constituents within sandstone, and of rock fragment composition. Carbonate fragments are sparse compared to sandstones of the Cotulla domain. Metamorphic rock fragments and metamorphic quartz are more prevalent. No core was available for the

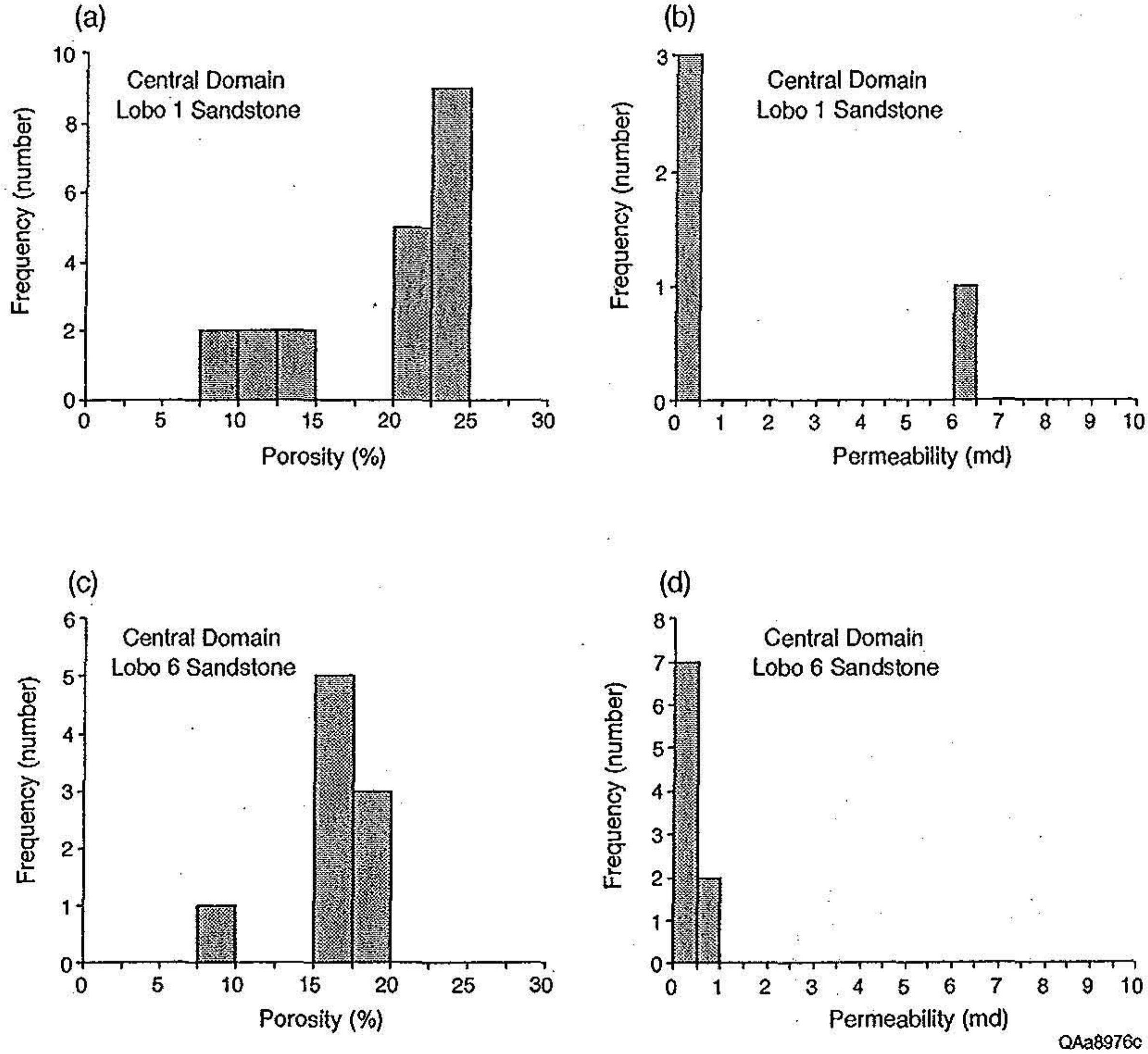

Figure 23. Porosity and permeability histograms from wells in the Central domain. Data from various unpublished industry sources.

Central domain, so no biostratigraphic or diagenetic analyses were carried out. No findings on these topics for Central domain sandstones have been cited in published literature.

Average gas permeability measured at net overburden pressure for a small suite of the Wilcox Lobo sandstone samples is about 8 md (based on compilation of unpublished industry data). Porosity and permeability measurements from selected industry wells are summarized in figure 22.

Basement Structures and Salt Tectonics

A characteristic of the Central domain is the shifting dominant strike of normal faults from northeasterly patterns typical of the Cotulla domain to northwesterly trends characteristic of the Burgos Rim domain. In this zone of transition, intricate crosscutting fault patterns are evident (fig. 24). In addition to the

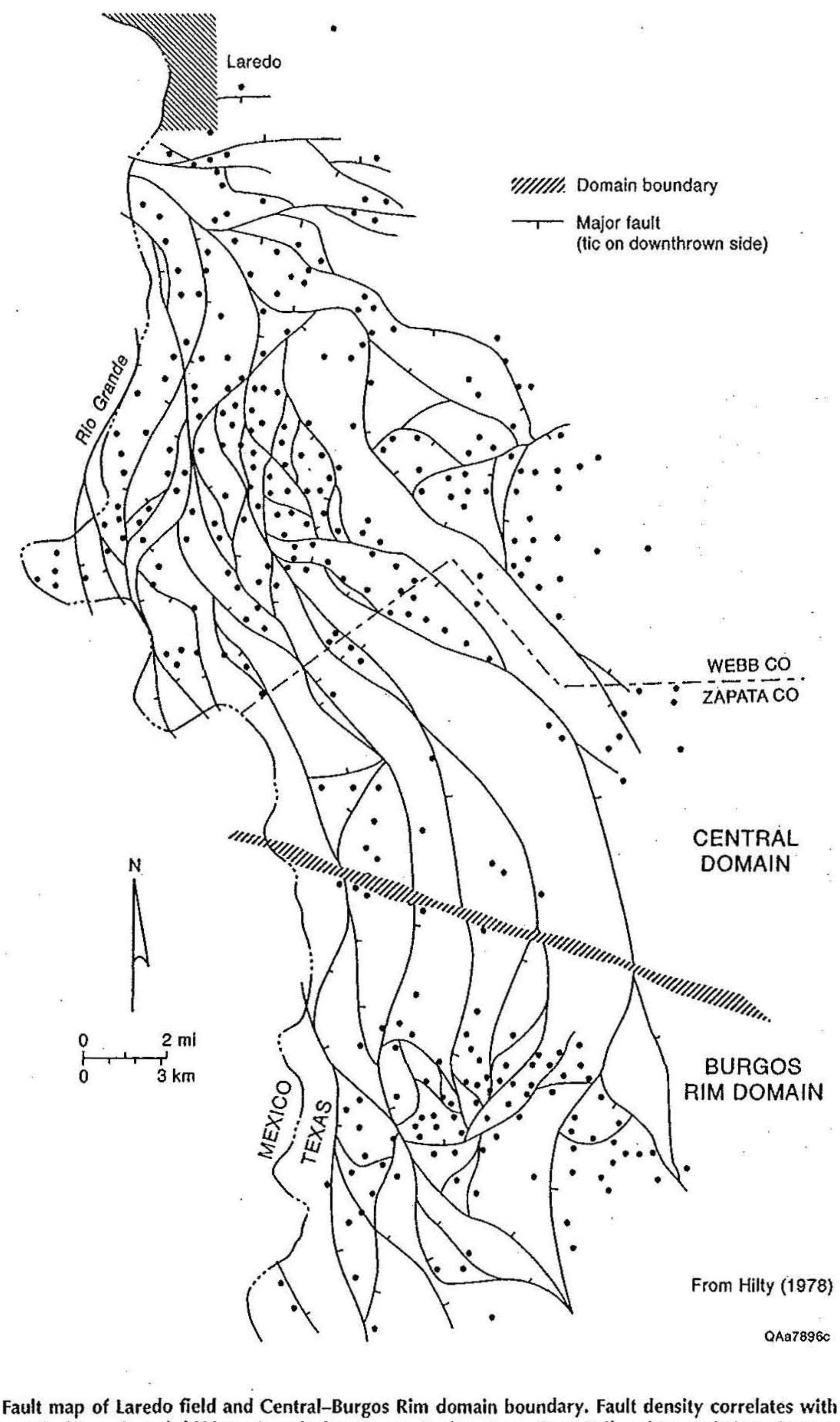

Figure 24. Fault map of Laredo field and Central–Burgos Rim domain boundary. Fault density correlates with well density. Note dominant fault trends and shifting minor fault patterns. Fault patterns from Railroad Commission of Texas (1980).

influence of the overall basin shape and Lobo gravity slide movement on fault trends, basement structure and salt tectonics may play a marked role on structural style in the Central domain.

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 (fig. 25), and these features of the Central domain are evident in Lobo producing intervals, as depicted on several published maps and maps on file at the Railroad Commission. Public-domain gravity and magnetic data indicate that the same dominant grains exist for basement structure in the Central domain. High-altitude images also reveal cross faults and joints having northeast strikes. Published maps and Railroad Commission open-file reports show that both of these grains are evident in the Lobo producing interval in the Central and Burgos Rim domains.

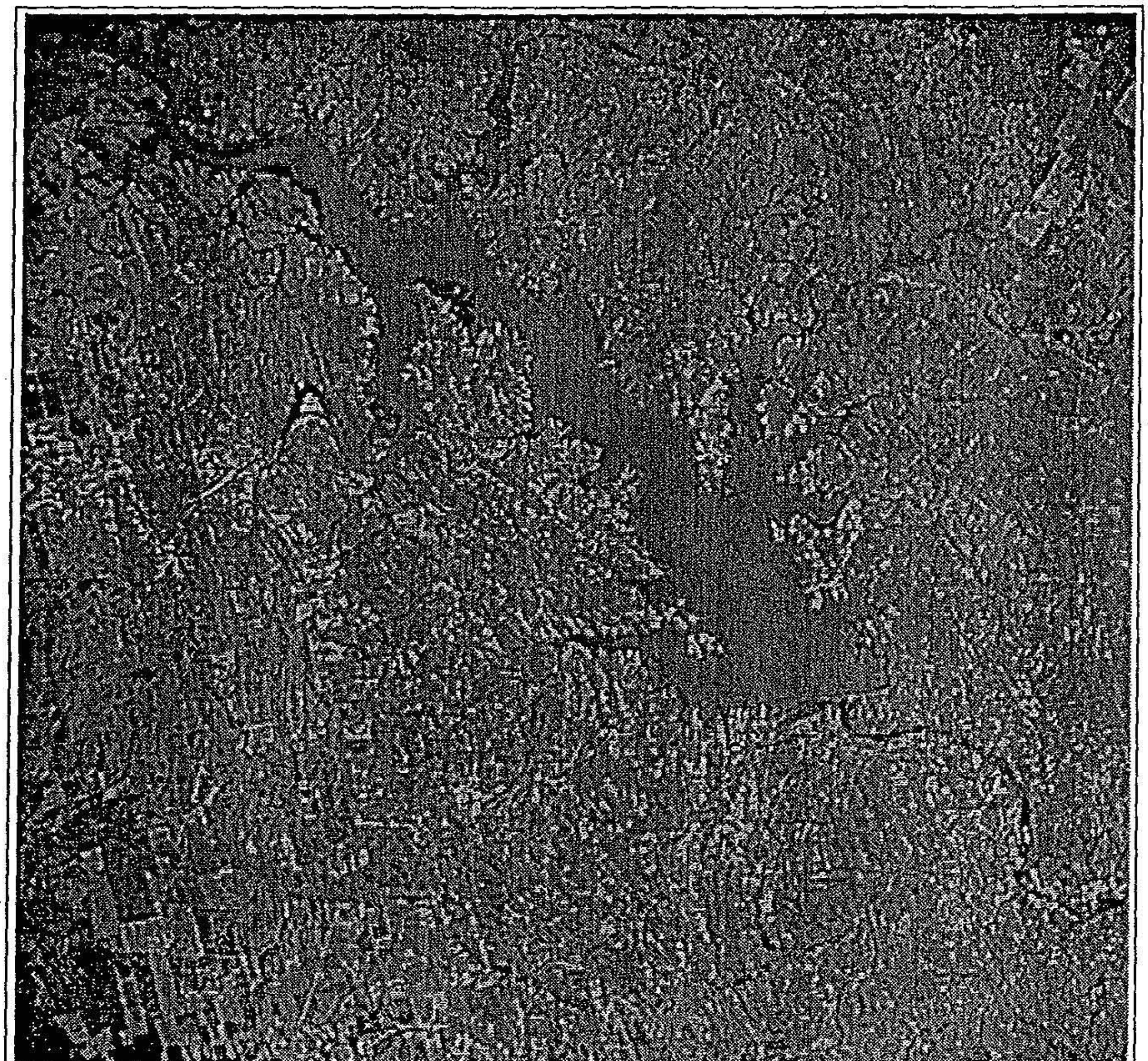

Figure 25. Shuttle photograph of part of the Lobo trend showing broad fold and features interpreted to be fault traces. Falcon dam and Rio Grande in upper right.

These observations suggest that high-resolution imagery, in conjunction with potential fields 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 Central domain is characterized by salt anticlines and isolated salt domes. For example, Lobo gas production at Pescadito is associated with a salt dome. We interpret basinward movement of evaporites, primarily salt, to be involved in initiation of the Lobo gravity slide.

Burgos Rim Domain

Tectonic Setting

The Burgos Rim domain includes the southern part of the Lobo trend in Zapata County and extends southward into Mexico (figs. 8, 26, 27). The Burgos Rim domain is characterized by north- to northwest-striking normal faults and east- to southeast-plunging low-amplitude folds. These structures resulted from interaction between gulfward gravity extension and northeast-directed Cordilleran compression. The western boundary of the Burgos Rim domain, which lies entirely in Mexico, occurs where Lobo shoreface and shelf facies grade into coastal-plain facies (fig. 27). Compressional deformation was most intense along this western boundary (Perez Cruz, 1992). The eastern boundary is the Upper Wilcox growth fault trend. To the north the Burgos Rim domain grades into the Central domain, but the southern boundary in Mexico is undetermined.

Despite proximity to the Cordilleran belt, gravity-driven tectonics still played a key role in the formation of the Burgos Rim domain. During the Late Cretaceous and early Paleocene, thick marine clastic sequences filled a subsiding foredeep basinward of the fold–thrust belt, forming an unstable platform across which Lobo depositional systems prograded. As was the case in the Cotulla domain, loading-induced gravity sliding toward the open Gulf of Mexico to the east deformed Lobo sandstones. Alternating episodes of deposition, deformation, and erosion occurred. In contrast to the Cotulla domain, however, in the Burgos Rim domain, episodes of northeast-directed compression also occurred, superimposing southeast-plunging anticlines on north-striking normal faults.

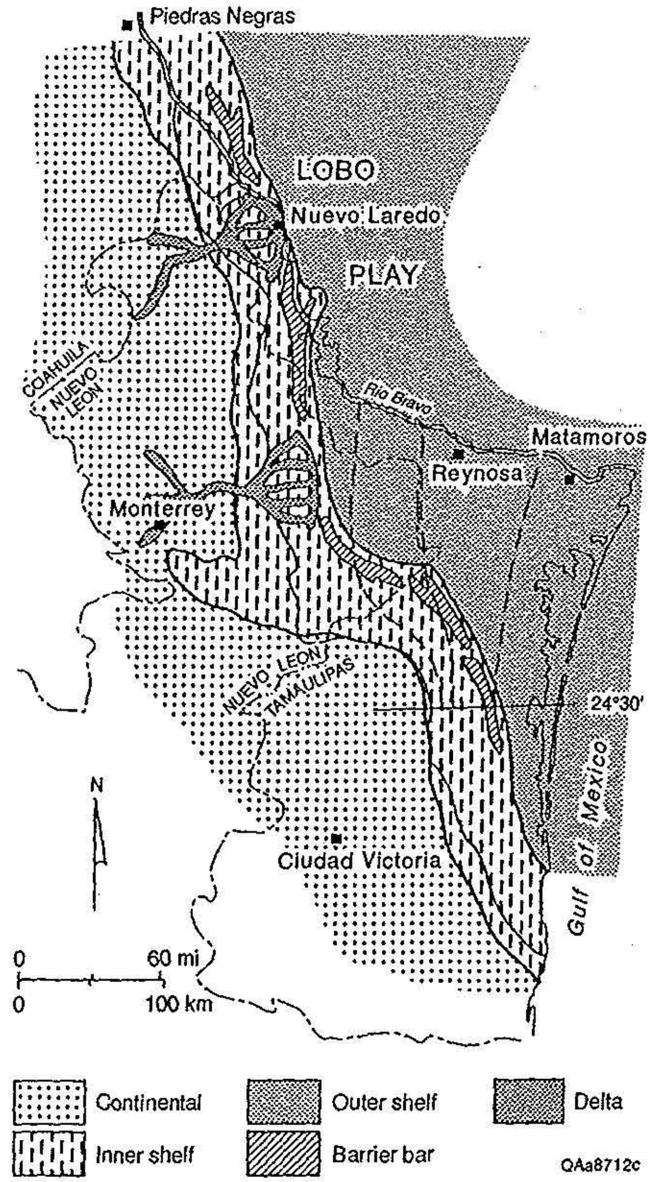

Figure 26. Regional patterns influencing the Burgos Rim domain. Fluvial systems crossing narrow shelf. Early Paleocene paleogeography of Burgos Basin. During Midway deposition, virtually all the area east of the present Rio Grande occupied an outer shelf setting. (From Echanove, 1986.)

The Burgos Rim domain contains localized fault-bounded basins holding overthickened Lower Wilcox (Lobo) and Middle Wilcox intervals. Interacting episodes of compression and extension may have mobilized underlying plastic salt and shale and enhanced load-induced subsidence near the shelf edge, creating local depocenters. In Zapata County several large gas reservoirs lying within these depocenters were, according to Railroad Commission records, originally thought to be in Lobo sandstones but are now known to be in downfaulted uppermost Paleocene or Middle Wilcox sandstones.

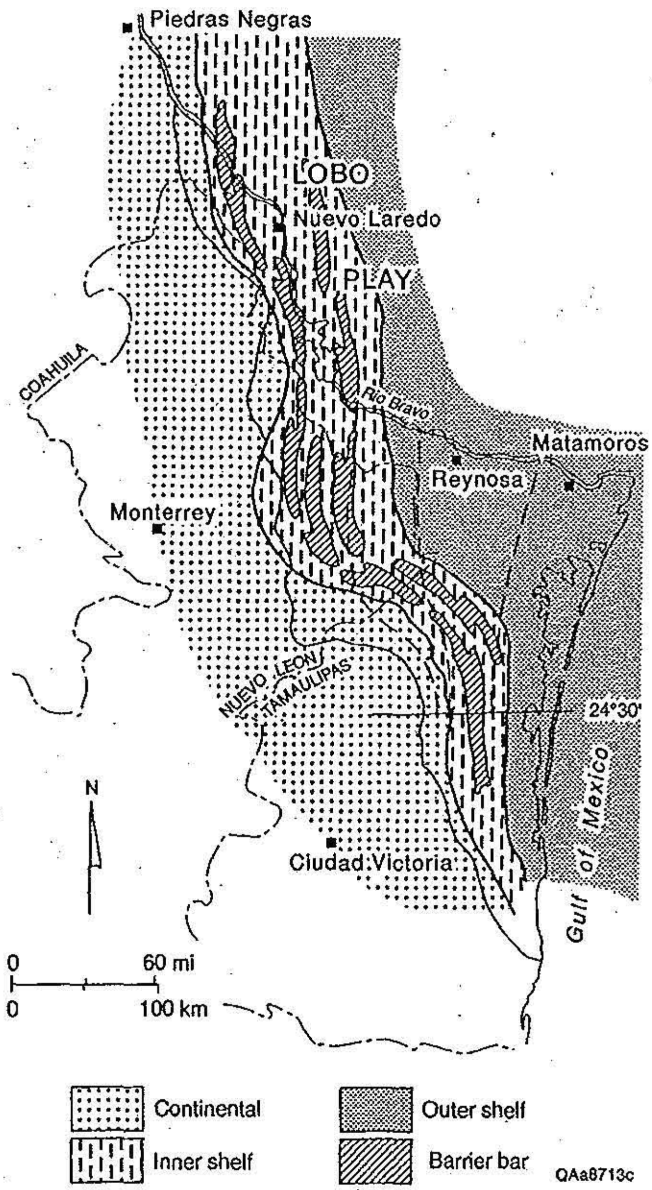

Figure 27. Regional patterns influencing the Burgos Rim domain. Shoreline-parallel depositional environments. Late Paleocene to earliest Eocene facies of the central and Burgos Rim domains and adjacent Tamaulipas and Nuevo Leon. (From Echanove, 1986.)

Paleogeography

The paleogeography of the Burgos Rim domain was distinctly different from that of the Cotulla domain to the northeast, and these differences extend beyond contrasts in the orientation of faults and sandstone geometry due to differing basin-margin orientations. Proximity to the Cordilleran orogenic belt imparted some active-margin-type features to this part of the Lobo depositional basin. Relatively narrow continental shelf and coastal plain areas were backed by rising highlands to the west. To the east, however, the gravitationally unstable shelf margin and slope persisted. The Lobo shelf had a northward to northwestward orientation in the Burgos Rim domain (fig. 8). Sediment source areas were the Cordilleran highlands to the west and southwest (fig. 27).

Owing to proximity to source areas and dip-oriented transport systems, Lobo depositional systems in the Burgos Rim domain included both strike- and dip-oriented elements. Although the depositional setting in the U.S. part of this domain was marine shelf, dip-oriented (southeast) channel sandstones have been mapped (Henke, 1982). These channel sandstones were probably deposited either in deltaic distributaries or submarine fans on the outer shelf. Strike-oriented depositional elements probably included delta-flank shoreface and shelf bar.

Reservoir Geometries

Fault compartmentalization is significant in the Burgos Rim domain (fig. 28). However, regional depositional patterns that influence this domain may make stratigraphic compartments common.

Internal stratigraphically controlled high-permeability compartments and low-permeability flow barriers are elongated in varying directions in the Burgos Rim domain, reflecting deposition in shoreface, shelf, and channel environments. Because Lobo depositional systems throughout the play include mainly strike-aligned shelf elements, dominant stratigraphic elongation is probably north to northwest. East- to southeast-oriented stratigraphic elongation, however, must be common in many Burgos Rim reservoirs.

Since depositional continuity is generally greater than structural continuity in the Lobo, most reservoirs are bounded externally by fault planes and surfaces of erosion. Burgos Rim fault-bounded compartments are elongated north to northwest, but fold axes trend southeast. Fault-segmented anticlines, for example, may contain a dip-oriented series of reservoirs, each within a strike-elongate fault block. Erosional truncation, which further modified reservoir geometries, may have had an irregular southeast grain, reflecting valley incision during sea-level lowstands. Thus, Burgos Rim domain reservoirs can be expected to display a range of shapes and orientations, but two dominant directions of elongation should emerge: north to northwest and southeast.

Lower Wilcox Core Study

We conducted thin-section, palynologic, and foraminiferal biostratigraphic analyses of the Wilcox interval cored in the Amerada Hess No. 10 Haynes well, Los Mogotes field, Zapata County (fig. 5). Our biostratigraphic data show this interval to be upper Paleocene, and it underlies a regionally extensive shale that we interpret to mark the Lower Wilcox–Middle Wilcox boundary. We interpret the sandstone to be part of an expanded Paleocene section within the Burgos Rim domain, as discussed in detail by Barker and Berggren (1977), that overlies the conventionally defined Wilcox Lobo. Informal terms such as "Charco" have been applied to this section by operators in the trend. The findings described below suggest that Paleocene Wilcox sandstones above the conventionally defined Lobo in the Burgos Rim domain and Lobo sandstones such as those in the Cotulla domain are compositionally and diagenetically very similar.

The Burgos Rim domain also contains Middle Wilcox sandstones that overlie or that are juxtaposed with the Wilcox Lobo in downfaulted blocks. They may in some instances be difficult to distinguish from expanded upper Lower Wilcox sections above the conventionally defined Lobo interval. The Middle Wilcox is an important gas producer in its own right, but nothing has been published about the Middle Wilcox in this area.

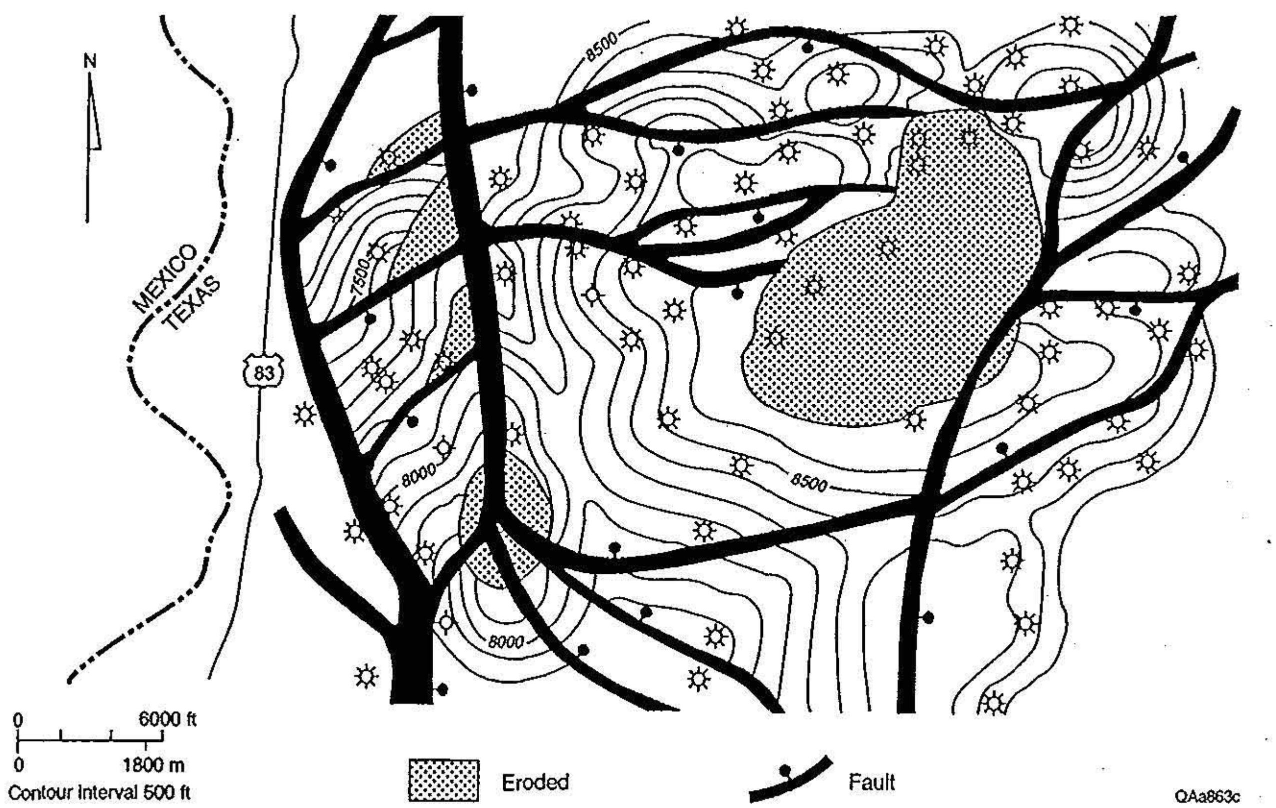

Figure 28. Structure map of faulted Wilcox Lobo reservoir (Lobo 1, J. C. Martin field, Zapata County). Intersecting northwest and northeast fault systems may produce characteristic fault-compartment shapes in the Burgos Rim domain. Map from O'Brien and Freeman (1979).

Biostratigraphy

As with the Forest Oil No. 4 Winch well in the Cotulla domain, cores from the Amerada Hess No. 10 Haynes well were sampled for palynologic and foraminiferal analyses. Palynomorphs (fair to poor preservation) are yellowish-brown to brownish-yellow, indicating 3.0 to 4.0 on the Staplin color scale of organic maturity. Both pollen and foraminifera (incomplete preservation; calcareous foraminifers not preserved) recovered from this core indicate deposition of the sands in a middle to outer shelf environment. Biostratigraphic analysis confirmed that the Paleocene Lower Wilcox sandstones in the Haynes well are all younger than the Lower Wilcox Lobo sandstones cored in the Winch well in the Cotulla domain.

Floral assemblages do change over the cored Wilcox interval and, with more analyses, it should be possible to discern if changes correspond to zones that could be used in sandstone identification and correlation. The foraminiferal population in this well is dominated by agglutinated forms, which are largely unsuitable for zonation; calcareous forms may have been dissolved, or deposition may have been in cloudier waters (B. Desselle, oral communication, 1994).

Composition

Nine Lower Wilcox sandstone core samples from the Amerada Hess Haynes No. 10 well were examined for texture, composition, and diagenetic history by means of standard thin-section petrography. 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 visibly clean (minimal detrital clay matrix) and extensively cemented sandstone intervals and are thus representative of reservoir sandstones.

Similar to the Wilcox Lobo sandstone samples described in our study, the Lower Wilcox samples are uniformly very fine grained sandstones. Samples range from poorly to moderately well sorted; most clean sandstones are moderately sorted. Sand grains are angular to rounded.

Lower Wilcox sandstones from the Haynes well are mineralogically immature, and most samples are classified as feldspathic litharenites in the sandstone classification of Folk (1974), although considerable range in composition is evident (fig. 29; table 4). All samples are quartz-grain dominated. The average composition of essential framework grains (normalized to 100 percent) from all core samples is 65 percent quartz, 16 percent feldspar, and 19 percent rock fragments ($Q_{65}F_{16}R_{19}$). Plagioclase is the only feldspar observed in the samples, composing 7 to 17 percent of whole-rock volume. Rock fragments occur in two categories: metamorphic (MRF) and sedimentary (SRF) types. Sedimentary rock fragments are the most abundant lithic type and comprise shale, chert, and rare micritic limestone, but low-rank metamorphic rock fragments are an important compositional element. Metamorphic rock fragments include phyllite and slate. Mean percentage of whole-rock volume for primary framework grains from the Haynes core samples is quartz (42.3), plagioclase (10.4), SRFs (10.4), and MRFs (2.6).

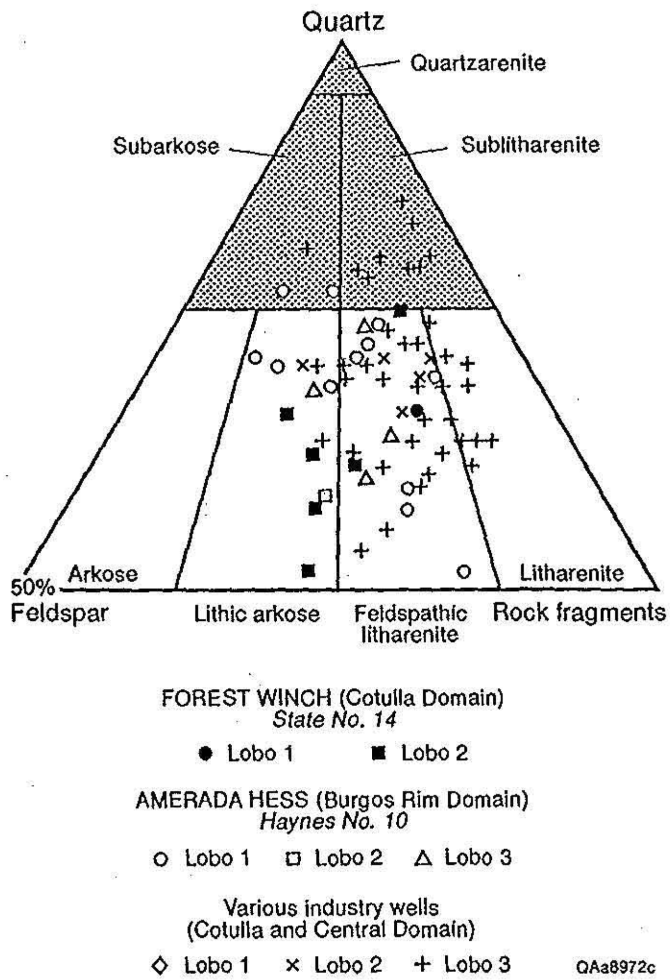

Figure 29. Composition of sandstones from all three domains subdivided by Wilcox Lobo sandstone interval.

Authigenic cements and replacive minerals collectively constitute between 15.0 and 39.5 percent of the whole-rock volume in the sandstone samples, with a mean value of 26.7 percent. Authigenic quartz, ankerite, chlorite, ferroan calcite, pyrite, and ilmenite occur in Middle Wilcox sandstone samples. The primary cements (ferroan calcite, chlorite, quartz, and ankerite) have mean whole-rock volumes of 12.9, 6.4, 5.3, and 2.1 percent, respectively.

Table 4. Petrographic analyses of Wilcox Lobo sandstones from the Amerada Hess Haynes No. 10 well, Zapata County, Texas. Values given in percent of whole rock volume.

Constituent	Range (%)	Mean (%)
Framework grains		
Quartz	37.0 to 46.0	42.3
Plagioclase	7.0 to 17.0	10.4
SRF[1]	6.0 to 20.5	10.4
MRF[2]	0.5 to 5.5	2.6
Other[3]	0.5 to 3.0	1.3
Cements		
Fe-calcite	0 to 37.5	12.9
Chlorite	0 to 18.0	6.4
Quartz	0 to 10.5	5.3
Ankerite	0 to 3.5	2.1
Matrix	0 to 6.0	2.0
Primary porosity	0 to 1.0	0.4
Secondary porosity	0 to 8.5	3.8

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

Diagenesis

The primary diagenetic events in the burial history of Lower Wilcox sandstones from the Haynes well, as they were in Lobo sandstones from the Winch well, 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 plagioclase 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 18 percent. Chlorite, the first cement to form in Paleocene Wilcox sandstones, is mostly a grain-rimming cement but also fills a small percentage of intergranular pore space (fig. 30). Iron-rich chlorite, derived from a higher proportion of unstable grains in this setting, may lead to the development of lower preserved porosity in some areas. Reactive clay cements also may be an important issue in these reservoirs.

Quartz cement has a whole-rock volume that ranges from 0 to 10.5 percent. Quartz cementation postdated formation of chlorite rims. Quartz cement formed by (1) development of relatively early quartz overgrowths 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 Lower Wilcox 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. Mapping sandstone grain provenance with advanced techniques could clarify where such zones predominate (fig. 31).

Ankerite has a range of whole-rock volume from 0 to 5 percent. Ferroan calcite, another carbonate cement, is by far the dominant cement in four of the nine samples. Ferroan calcite volume varies from 0 to 37.5 percent. 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 they 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

Porosity observed in Lower Wilcox thin section samples from the Haynes core is almost all secondary, which varies from 0 to 8.5 percent. Average total porosity of samples is 4.2 percent. Cements and ductile, compaction-deformed SRFs and MRFs occlude most visible porosity. Primary porosity was observed in four samples 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).

Stress Regime and Other Attributes

Although data within the Lobo play are lacking, evidence from adjacent parts of the Gulf Basin (Zoback and Zoback, 1989; Langford and others, 1992) suggests that the Cotulla domain is in the Gulf Basin stress province. However, data to characterize stresses in the Central and Burgos Rim domain are lacking, and the setting of these domains suggests that extrapolation from the Gulf Basin is not justified. Stress direction information is vital information for hydraulic fracture treatment design, especially in a highly faulted area where compartment boundaries may be close to treatment wells. In comparable tectonic settings elsewhere along the margin of the (inactive) Cordilleran thrust belt, drastic shifts in in situ stress directions have been identified (Laubach and others, 1992).

The tectonic setting of the Burgos Rim domain implies that this domain may contrast with the Cotulla, and to a lesser extent with the Central domain in burial and stress history. Such contrasts could have implications for diagenetic history, patterns of fluid flow and trapping, and current in situ stress.

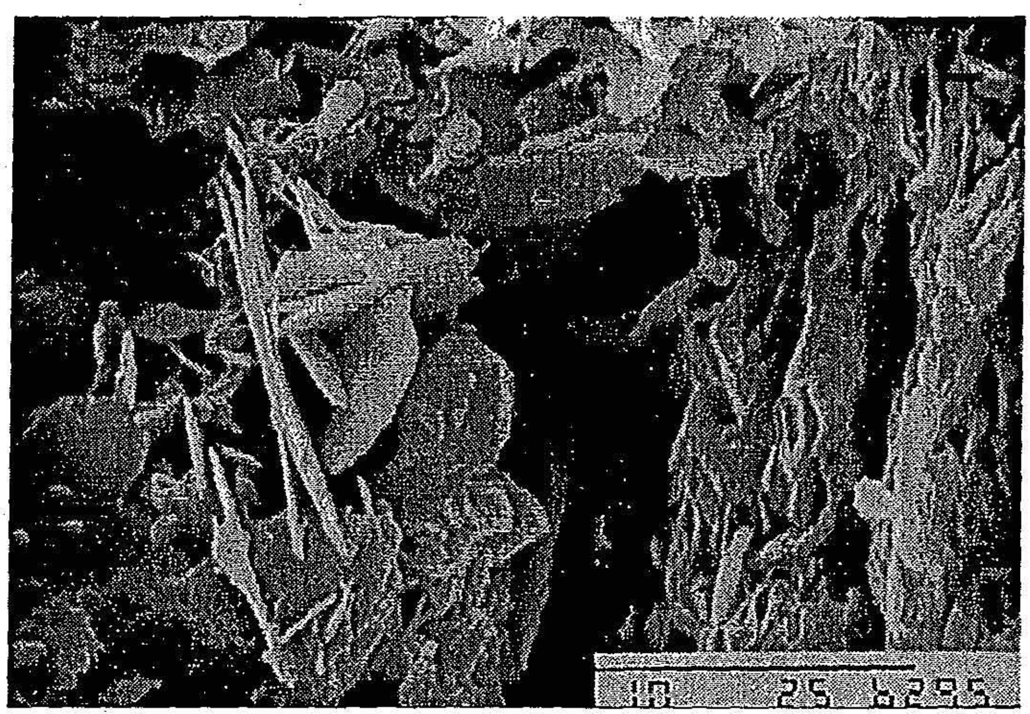

Figure 30. Characteristic habit of iron-rich chlorite in pore of sandstone, characteristic of the Cotulla domain.

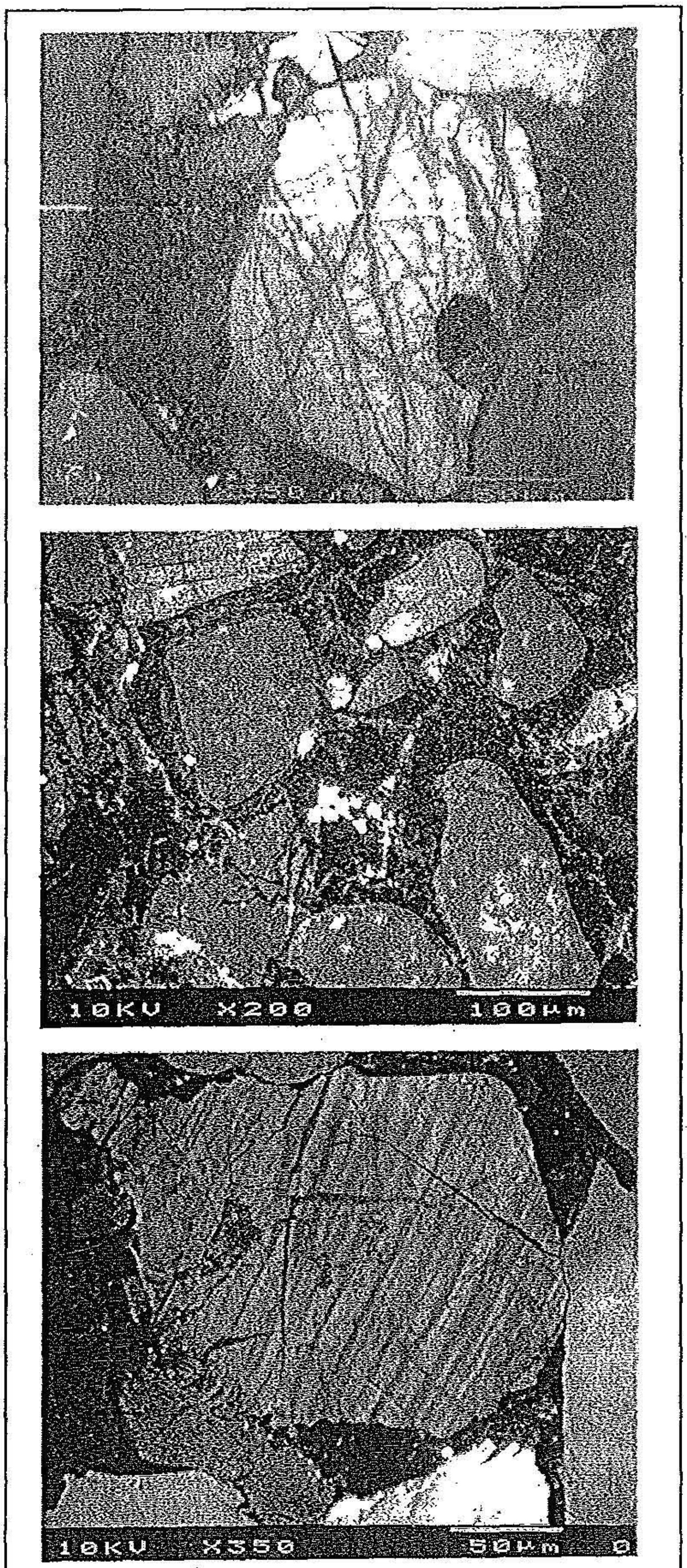

Figure 31. Example of quartz grain imaged using scanned cathodoluminescence. This approach could yield information on Wilcox Lobo source areas and depositional patterns.

Of Lobo domains, the Burgos Rim domain has the least evidence of salt tectonics. Evaporites within the domain are at great depth and appear to exert little or no influence at the Lobo level. This circumstance may have implications for the style of faulting in this domain. Predictable patterns of lenticular fault blocks (figs. 32 and 33) may be more prevalent in the southern and western Burgos Rim domain.

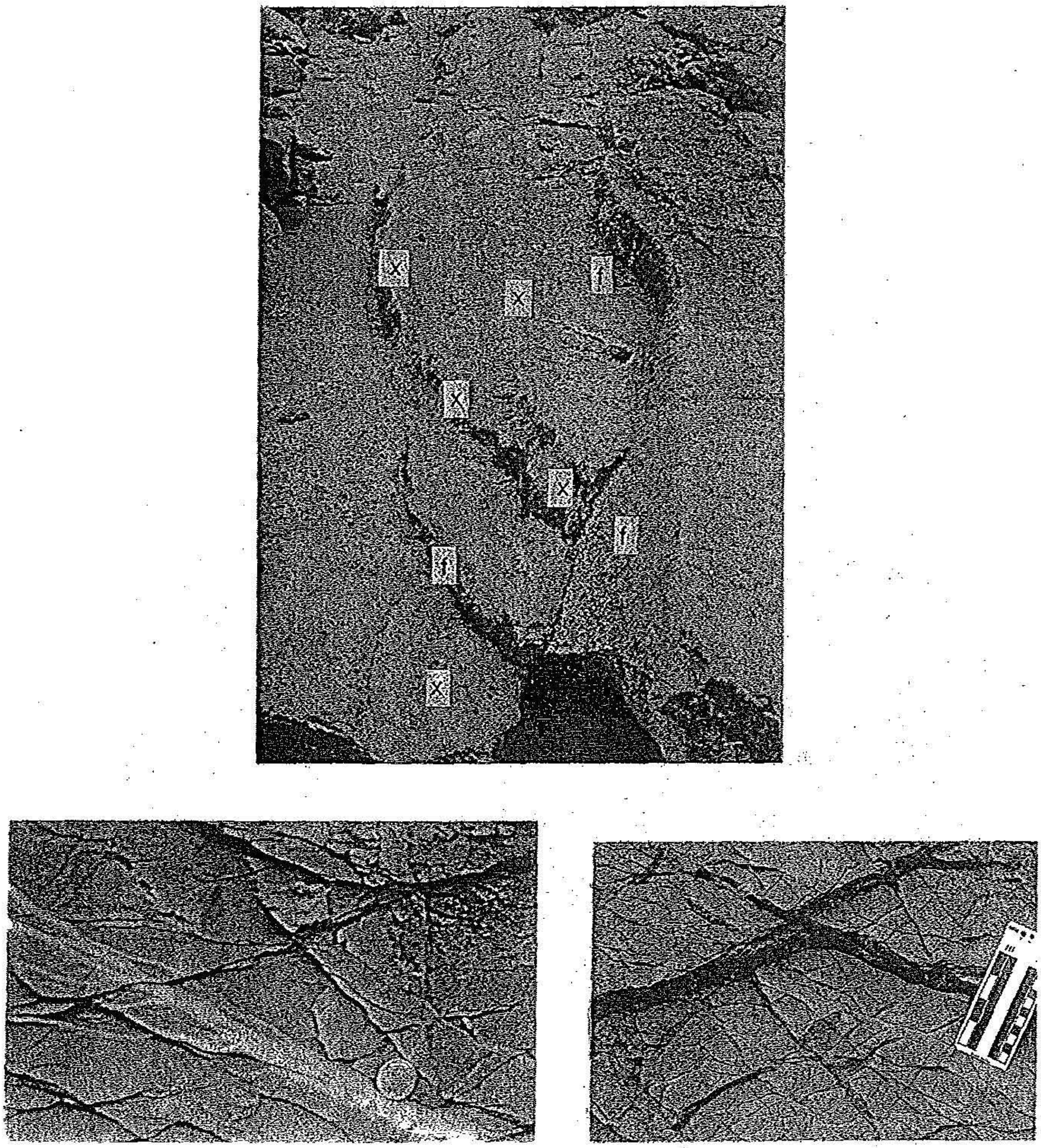

Figure 32. Analogs of Wilcox Lobo normal faults. (a) Outcrop example of normal fault "compartments" (x) near the termination of a master fault (f) illustrating how small and large fault blocks can be genetically associated. In the Lobo, fault-bounded compartments that are near the margins of current drilling targets may be accessible in the future with directional drilling. (b) Fault patterns in plan view.

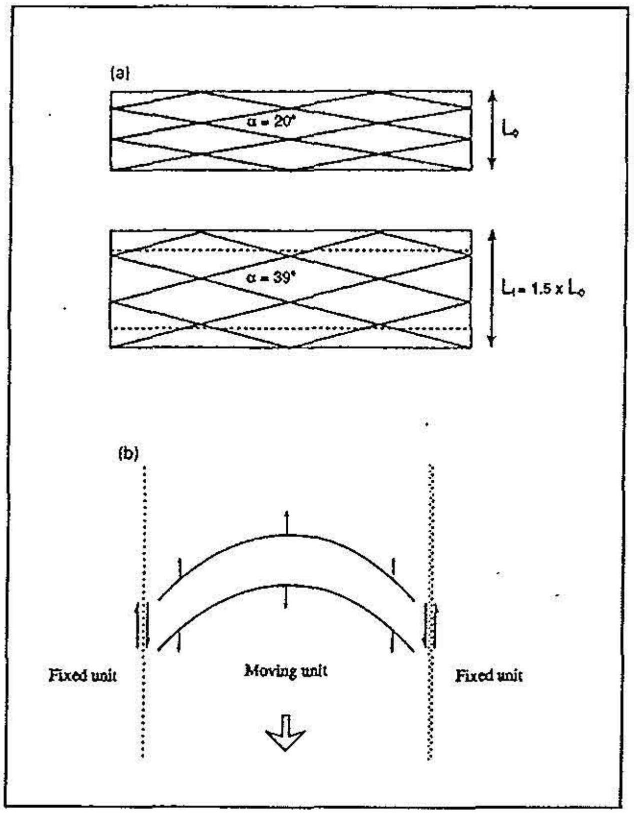

Figure 33. Evolution of Wilcox Lobo domains may affect fault patterns, producing characteristic fault-block (and compartment) shapes. (a) Increase in obliquity between fault traces induced by uniform uniaxial stretching (map view). (b) Fault trace curvature induced by lateral friction. From Laubach and others (1992) after Vendeville (1987).

Integrated Domain Characterization

Knowledge of the basic attributes of the Lobo domains (table 1) together with the implications of variations in the tectonic framework can be effective tools for inferring Lobo reservoir properties where available data are limited. In the Lobo play, depositional, compositional, and structural patterns are complex and difficult to document regionally. The domains concept allowed us to maximize information derived from sparse regional data and to make reasonable predictions about reservoir geology (table 5).

Depositional Elements

The seven Lobo sandstone zones are laterally continuous but are composed internally of discontinuous sandstone lenses interbedded with thin shales. Regional distribution patterns of such lenticular sandstones are key unknowns in the Lobo play. Strike-elongate lobes and dip-oriented channels are both common sandstone-lens geometries and are found in all three Lobo domains. Strike-elongate sandstone lobes are probably best developed on the broad shelf of the Cotulla domain, whereas dip-oriented channel sandstone trends are probably most abundant in the Burgos Rim domain, which has a narrow shelf backed by rising highlands.

Varying or episodic influence of the compressional and extensional tectonic regimes over time may be reflected in differences in sandstone development among the Lobo zones. The Lobo 6 zone, for example, has widespread continuity across the play area (fig. 5) and displays little variation in thickness that can be attributed to syndepositional structural deformation. Therefore, the Lobo 6 zone must have been deposited during a period of relative tectonic quiescence and shelf stability. The Lobo 1 zone, in contrast, also has

Table 5. Predictions and implications drawn from Lobo domain model.

Reservoir Attribute	Cotulla Domain	Central Domain	Burgos Rim Domain
Sand-body geometry			
A. Predictions	Dominantly lobate and strike-oriented, larger than fault spacing	Transitional	Dominantly lenticular and dip-oriented
B. Implications	Structural compartments dominant	Mixed structural and stratigraphic compartments	Stratigraphic compartments common
Sandstone composition			
A. Predictions	Fewer unstable grains	Transitional	More unstable grains
B. Implications	Higher preserved porosity	Variable preserved porosity	Lower preserved porosity
Tectonics			
A. Predictions	Fewer compressional structures, larger fault blocks	Local compressional structures, variable fault block size	Common compressional structures, smaller fault blocks
B. Implications	Simple lenticular NE-trending fault blocks	Irregular to equant fault blocks, variable orientations	Complex N-NW-trending fault blocks, E-SE-trending anticlines

widespread continuity but displays large thickness variations depending upon structural setting. In the southern part of the Central domain and in the Burgos Rim domain, the Lobo 1 thickens greatly into localized syndepositional subsidence basins.

Because of the expected consistency of general depositional patterns, domain-specific depositional models, based on well and 3-D seismic data, could be constructed and used to characterize sand-body geometries throughout each domain. Narrow dip-oriented channel sandstones may represent an underexplored target in the Lobo, where exploration has been focused on structural objectives, and 3-D seismic data are especially well suited for resolving complex channel patterns. Because our domain paradigm predicts channels to be most abundant in the south, a strategically placed 3-D survey, supplemented with core and log data, could be used to build a model of Lobo channel sandstone reservoirs that could be used to guide exploration and development throughout the Burgos Rim domain.

Compositional Elements

Sandstone compositions are expected to vary across the Lobo play in response to changing source areas and variable amounts of reworking in the depositional environment. The position of the Lobo complex near the boundary between the North American craton and the Cordilleran belt (fig. 7) implies that minor shifts in direction of sediment input might result in significant differences in sediment composition. Reworking in the depositional environment tends to selectively remove unstable components, such as rock fragments, and results in more homogeneous, quartz-rich compositions.

Comparison of our Lobo work with regional studies of Wilcox sandstone composition along the Texas Gulf Coast (Loucks and others, 1986) suggests that Lobo sandstones contain slightly more rock fragments and slightly less feldspar than do other Wilcox sandstones. This compositional difference can be attributed to metamorphic and volcaniclastic debris coming from the Cordilleran belt. Typically, abundant rock fragments negatively impact reservoir quality by deforming ductilely and occluding porosity. Within the Lobo play, sandstones in the Burgos Rim domain might be expected to contain the most rock fragments, because the Cordilleran source area is most influential in this domain. Furthermore, relative proximity to source area in the Burgos Rim domain would limit reworking during transport, enhancing the survival potential of rock fragments, including unstable metamorphic and volcanic rock fragments that are susceptible to breakdown into reservoir-damaging clay minerals. This may account for the relatively higher proportion of unstable rock fragments and clay-mineral cements in the limited samples obtained to date from the Burgos Rim domain.

The tectonic setting of the Lobo play suggests that different sediment source terrains and regional influences on sedimentation may exist for various parts of domains. We compared compositional data for areas approximately coinciding with (1) the Central domain and southwestern part of the Cotulla domain and (2) the central and northeastern parts of the Cotulla domain (fig. 8) because these areas are most likely to show the influence of tectonically controlled axial fluvial sediment input and sediment input derived from along-shoreline sources.

Data from the Forest Winch No. 4 well and from unpublished industry sources suggest that sandstone composition varies between the Cotulla and Central domains. Sandstones from both data sets (figs. 12 and 22) are dominantly feldspathic litharenites. However, a significant portion of the Cotulla domain samples are sublitharenites and litharenites and contain a larger percentage of quartz and lithic fragments, respectively, than samples from the Central domain (fig. 22). However, note that notably fewer samples are available for the Central domain. Thus, any conclusions regarding compositional variation between the two domains must be regarded as tentative until a similar number of samples for the two data sets can be compared.

Sandstone compositional variation is consistent with the hypothesis that sands from the Central domain and western Cotulla domain were in part derived from westerly or northwesterly source terrains, whereas those from the eastern Cotulla domain had dominantly more northerly sources. Sandstone-compositional data compiled for this study show greater compositional variation for sandstones from the Central domain and western Cotulla domain (fig. 13a) than that for the eastern Cotulla domain (fig. 13b). Compositional data from the eastern Cotulla domain are distinctly more clustered, although mean composition for both areas is about the same in the feldspathic litharenite range.

Such compositional differences could lead to differences in average reservoir properties. These differences are suggestive, rather than statistically significant, because the data set is small, and other important variables, such as degree of diagenetic modification of sandstone composition and the effects of local depositional setting, could not be accounted for using this data set. For example, as illustrated in figure 29, the compositional range of various Lobo sandstones is about as great as that evident among domains.

These results are intriguing not only because of the potential for diagnosing compositional controls on reservoir quality, but because of what these slight differences in sandstone composition may indicate about sedimentary transport patterns and the prospects for identifying subtle patterns of sandstone thickness variation. Such information is useful for interpreting 3-D seismic data and designing infill-well patterns. In this regard, recent advances in microscopic characterization of detrital quartz character by improved cathodoluminescence techniques (e.g., Milliken, 1994) could be useful for distinguishing and mapping sediment sources in this play. Figure 31 shows the type of detail in analysis of detrital quartz composition that can now be routinely obtained.

Structural Elements

Multiple phases of postdepositional deformation and erosion profoundly modified Lobo sandstone continuity. Erosional truncation segments sandstones that were depositionally continuous, compartmentalizing reservoirs. Erosional unconformities generally record interactions between tectonic compression and uplift and eustatic lowstands of sea level. Where the influence of eustatic sea-level changes is greatest, erosional unconformities might take the form of dip-oriented incised valleys on the exposed shelf. Where tectonic compression and uplift are greatest, unconformities might take the form of more localized truncations of uplifted blocks. Thus, the distribution and geometries of unconformity-bounded reservoir compartments are expected to vary systematically across the Lobo domains in response to varying tectonic setting.

A related issue is the map pattern of normal faults within the Lobo trend. Fault geometry, and thus reservoir compartmentalization and reservoir shape, may vary by domain. In addition to differences in general orientation, fault blocks in the various domains may have differing degrees of subsidiary faulting and different overall patterns depending on the domain in which they occur. Fault blocks in the Cotulla domain are expected to in general have simple lens-shaped geometry in plan view, reflecting uniaxial extension in a setting close to that of conventional Gulf Basin tectonics. Outcrop-scale analogs, such as those in figures 32 and 33, show large-scale examples of the characteristic appearance of such faults.

In the Central domain, several influences may have competed to produce more irregular or equant fault blocks. These include the abrupt change in overall basin shape manifested in shifting strikes of mapped faults, possibly the influence of salt tectonics, and, toward the western and southern side of the domain, an increased influence of faulting related to compressional tectonics superimposed on normal fault arrays of the Gulf Basin style. It is this latter influence that we speculate may play a role in fault patterns of the Burgos Rim domain.

The Burgos Rim domain contains east- to northeast-trending structural elements—faults and fractures—that contrast with the overall northerly structural grain defined by basinward extension. In view of the tectonic setting of the Burgos Rim domain and the timing of tectonism in the nearby orogenic belt, some of these inconsistent structural trends may be the result of compressional foreland-basin tectonics.

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, 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 Texas-Mexico 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 deformational belt may also have played a role in governing sandstone depositional patterns, source areas, and erosional history of the Lobo trend.

As a result of postulated foreland extension in the Burgos Rim domain, northeast-directed compressional tectonics could have created normal faults and fracture zones striking at right angles to the orogenic belt. In the Burgos Rim domain, this would tend to subdivide north- to northwest-trending extensional fault blocks. Observed repetition of section along apparent reverse faults in the Lobo has been ascribed to the gravitational collapse of unstable slump blocks (Long, 1986). Although tectonic reverse faults have not been recognized within the Lobo play, with available data, it is not possible to rule out that such faults exist as a result of active tectonics, either instead of or in addition to faults caused by slump tectonics. If present, such tectonic reverse faults should tend to be most prevalent in the western parts of the Burgos Rim domain.

Salt Tectonics

The timing, pattern, and style of Lobo deformation suggest that salt mobilization—possibly initiated by Laramide compressional deformation—may also have affected structural development of the Lobo trend.

Although the basal salt layer appears thin on seismic record sections (Ewing, 1986), it was apparently thick enough to become mobile in response to regional tilting during the Laramide. Although domains differ in the type of salt structure present, salt-tectonic processes operating in different domains may have been linked by the overall kinematics of salt and overburden movement. The domain most likely to have extensive effects of salt tectonics is the Central domain.

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 (tables 6 and 7) suggest that salt tectonics could have played a significant role in Lobo slump and fault development. Neogene slides that we interpret to be analogs for the Lobo have been described by Morton (1993; fig. 34). There are intriguing similarities, even to the bight in the shelf and basin margin, between the Lobo setting in the Rio Grande Embayment and the paleogeography of the East Texas Basin (figs. 35 and 36). This area may provide an analog for general geologic patterns in the Lobo; the advantage is that this area does not have the overprint of extreme extension that masks much of the regional geology in the Lobo play.

In the Rio Grande Embayment, some salt movement postdates Lobo deposition, as shown by salt domes at Pescadito (mid-Eocene, Yegua), Moca (late Eocene, Jackson Group), and elsewhere that pierce Wilcox Lobo strata. Several fields on the flanks of Pescadito dome yield gas from Lobo sandstones.

Our recognition of the possible role of salt mobilization in Lobo evolution presents the opportunity to use sophisticated salt tectonics models, which have been successfully applied to unraveling difficult structural problems in the deep-water Gulf of Mexico. Our results suggest that such models can be applied to unraveling the structural, and possibly the stratigraphic, evolution of the Lobo (figs. 37–40).

Table 6. Summary of common attributes of large-scale shelf-margin failures and overlying fills in the southwestern Gulf Coast Basin. From Morton (1993).

Attribute	Description
Relative dimensions and morphology	As much as 150-km-wide parallel to depositional strike, width commonly exceeds identifiable length, overall shape is amphitheater-like, concave basinward
Depositional setting	Broad, low-gradient, interdeltaic shelf platform and adjacent slope
Intrabasinal structural influence	Contemporaneous extension and reorganization of mobile sediments, may coincide with structural inversion of slope deposits
Basal discontinuity	Detachment surface occurs within thick interval of marine mudstones, discontinuity steps progressively higher stratigraphically landward, abrupt changes in surface elevation typically coincide with planes of deep-seated faults
Composition of slide and fill	Thick slope mudstones and thin slope sandstones overlain by thick shelf mudstones and upward-thickening shore-zone sandstones
Thickness of slide and fill	As much as 600 m including basal slide deposits, thickness decreases landward and basinward
Paleobathymetry of fill	50 m to greater than 200 m, decreases landward and upward in fill
Primary erosional and depositional processes	Initial failure of upper slope and shelf margin, repeated submarine excavation and depositional restoration
Phase of relative sea-level change	Can be initiated during any phase, the Neogene slides probably were initiated during late highstands, after flooding of the platform, but before substantial lowering of relative sea level
Basin equivalents	Mud-rich slope aprons and sand-rich submarine fans

Table 7. Attributes of late Paleocene Wilcox Lobo slide, Rio Grande Embayment.

Attribute	Description
Depositional setting	Narrow, low-gradient shelf platform; bordered by tectonic highlands in Mexico
Intrabasinal structural influence	Thin Jurassic evaporites dating from Gulf of Mexico opening; isolated salt structures on shelf
Basal discontinuity	Lobo slide: In shales of lower Midway (basal Paleocene), near top of Cretaceous. Deeper section: block faulting and rotation above detachment(?) surface at Jurassic salt level
Paleobathymetry of fill	Middle to outer shelf; Lobo and Stray sections contain no slope or deeper water fauna; closest deeper water deposition in late Paleocene is in Burgos Basin ~120 km to south
Sea level at time of slide	During transgressive phase of long highstand, influenced by tectonic subsidence
Possible triggering mechanism	Downslope movement of salt with gradual regional tilt (1 degree or less) in later stages of Laramide deformation

Our preliminary physical modeling of Lobo structures suggests that this approach can shed light on the kinematic evolution of Lobo fault blocks, leading to more definitive interpretation of cryptic fault patterns. Such insights can aid interpretation of 3-D seismic information, particularly for faults that are below the size that can be resolved by current seismic methods. Examples in figures 37 and 40 show how modeling can explain variable tilt and differential erosion and reworking of sands from fault blocks. Note the similarities of these features to those in seismic lines presented by Long (1986).

Geopressure

The Lobo interval of the Burgos Rim domain is generally geopressured and is within the Zapata geopressured geothermal fairway of Bebout and others (1982), who cite an average depth to geopressure of −10,700 ft. The 300-degree isotherm is encountered at −11,400 ft and the geothermal gradient in the area is about 2°F/100 ft (figs. 41 and 42). Where the section is shale-dominated, the top of geopressure is at depths between −8,000 and −10,000 ft, whereas in sand-

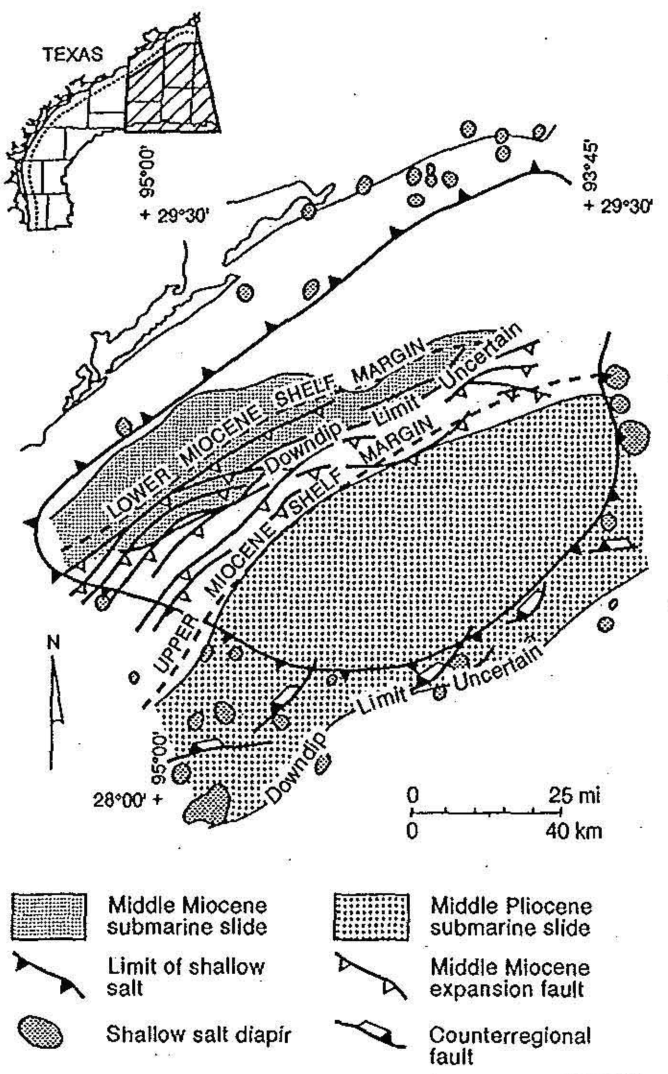

Figure 34. Example of Middle Pliocene submarine fan: analog for Wilcox Lobo. See text for explanation. From Morton (1993).

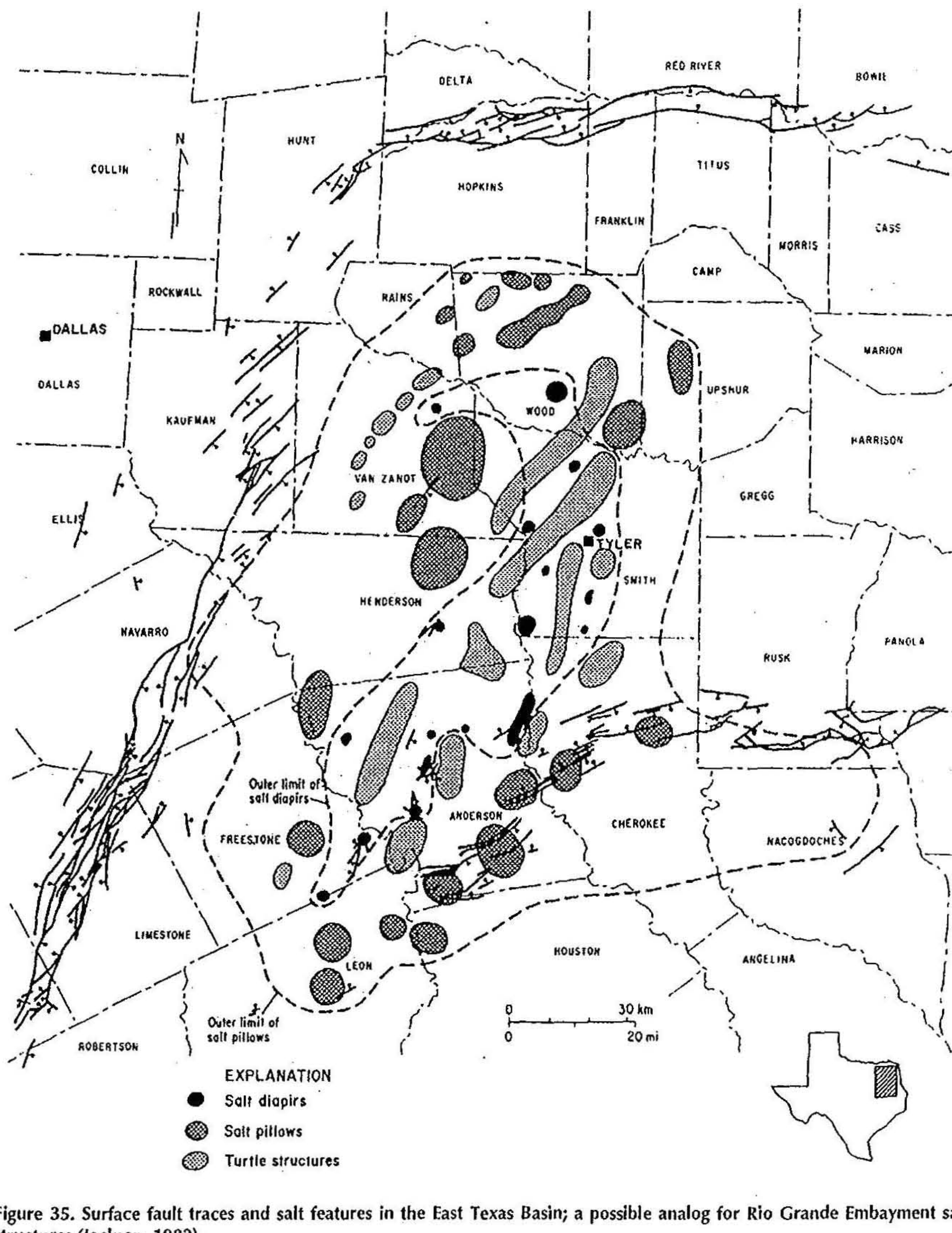

Figure 35. Surface fault traces and salt features in the East Texas Basin; a possible analog for Rio Grande Embayment salt structures (Jackson, 1982).

dominated sections the top of geopressure is deeper, between −11,000 and −13,000 ft. As can be seen on figure 41, depth to geopressure decreases across the trend from between −13,000 and −10,000 ft in the northern and western Cotulla and Central domains, to −8,000 ft or shallower in the northern Burgos Rim domain.

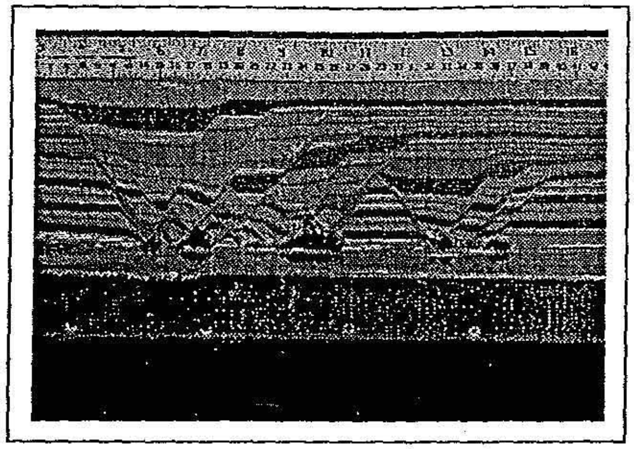

Figure 37. Cross section of structures produced in sand/silicone models of gravitational gliding on salt on an inclined substrate; downslope to right (B. Vendeville, unpublished data, 1994).

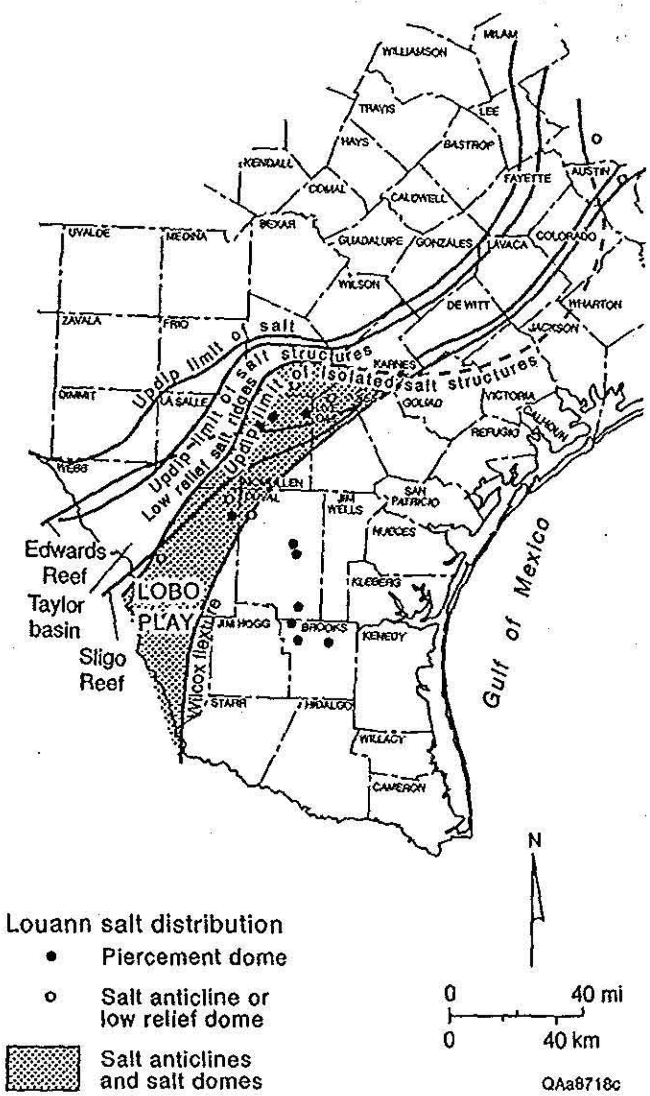

Figure 36. Distribution of salt tectonic provinces relative to the Lobo play area (Raring, 1986).

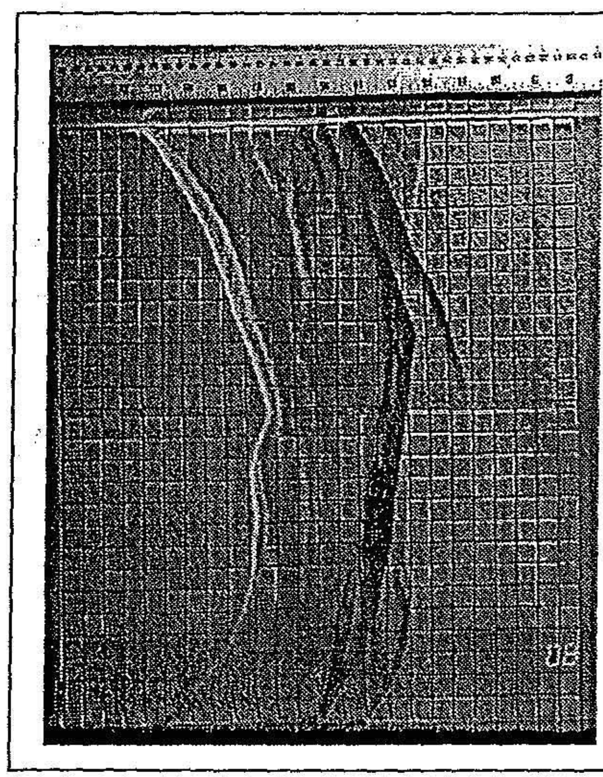

Figure 38. Map view of structures produced in sand/silicone models of gravitational gliding on salt on an inclined substrate; downslope to right (B. Vendeville, unpublished data, 1994). Compare fault pattern to those in maps of the Lobo slide area, particularly in the Central domain.

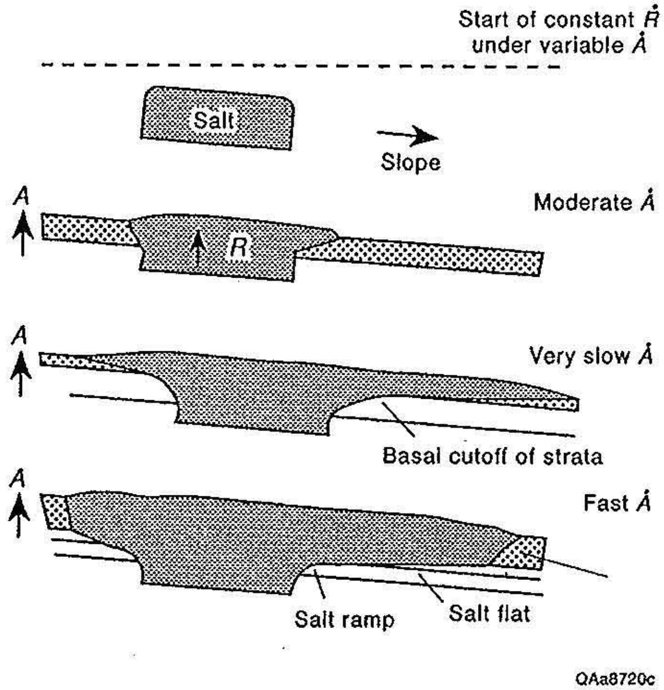

Figure 39. Asymmetric spreading of a passive salt sheet over or just below the sedimentary surface. Highly variable aggradation rate produces salt ramps, salt flats, and basal cutoffs along the base of the salt allochthon. A = aggradation, $\dot{A}$ = aggradation rate, R = salt rise increment, $\dot{R}$ = salt rise rate (Jackson and others, 1994).

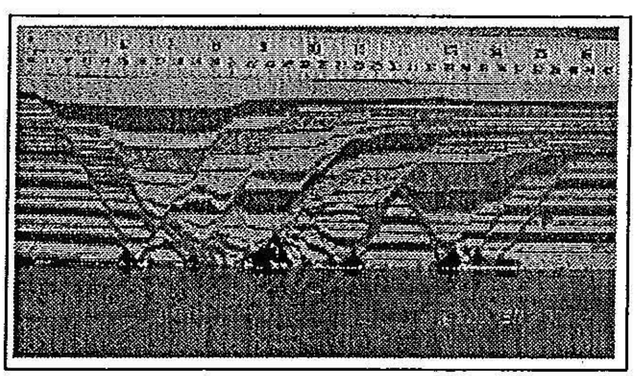

Figure 40. Illustration of how variations in sense of displacement, tilt, and sedimentary reworking of fault blocks can arise. Note variations in sense of fault displacement, tilt of blocks, and sediment redeposition (B. Vendeville, unpublished data, 1994). Detail of figure 37.

Productivity Controls

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. This section focuses on potential geologic controls on production that can be related to the special characteristics of each Lobo domain.

Historically, the Cotulla and Central domains have been more productive than has the Burgos Rim domain. In the former two domains, fields are generally more abundant, more closely spaced, and more prolific than in the latter. The Cotulla domain contains Big Cowboy, Carr, Gato Creek, Lundel, and Mujeres Creek fields, which combined have produced more than 572 Bcf of gas. Although the giant Laredo field (578 Bcf) dominates, the Central domain also contains several other large Lobo fields, such as Bashara–Hereford (136 Bcf), La Perla Ranch (359 Bcf), and McMurrey (311 Bcf). The Burgos Rim domain, however, currently contains only one big field—J. C. Martin (402 Bcf)—which is located near the boundary with the Central domain. The Burgos Rim domain also contains two large Middle Wilcox fields: Charco and Roleta.

Low historical Lobo production in the Burgos Rim domain, which can be attributed to geologic setting, may represent an underexploited opportunity; increasing exploration activity in this southern domain supports this assessment. The influence of compressional tectonics is strongest in the Burgos Rim domain, and the interaction between compression and extension there must have resulted in the greatest amount of structural complexity. In this region of intersecting northwest- and southeast-trending structures, fault densities and displacements are potentially greater, resulting in smaller reservoir compartments. As discussed above, depositional elements might be more lenticular, and sandstone compositions might be less mature. A better understanding of Burgos Rim structural and depositional elements, however, could lead to the development of powerful domain-specific exploration and development models and to the successful exploitation of overlooked reservoir compartments.

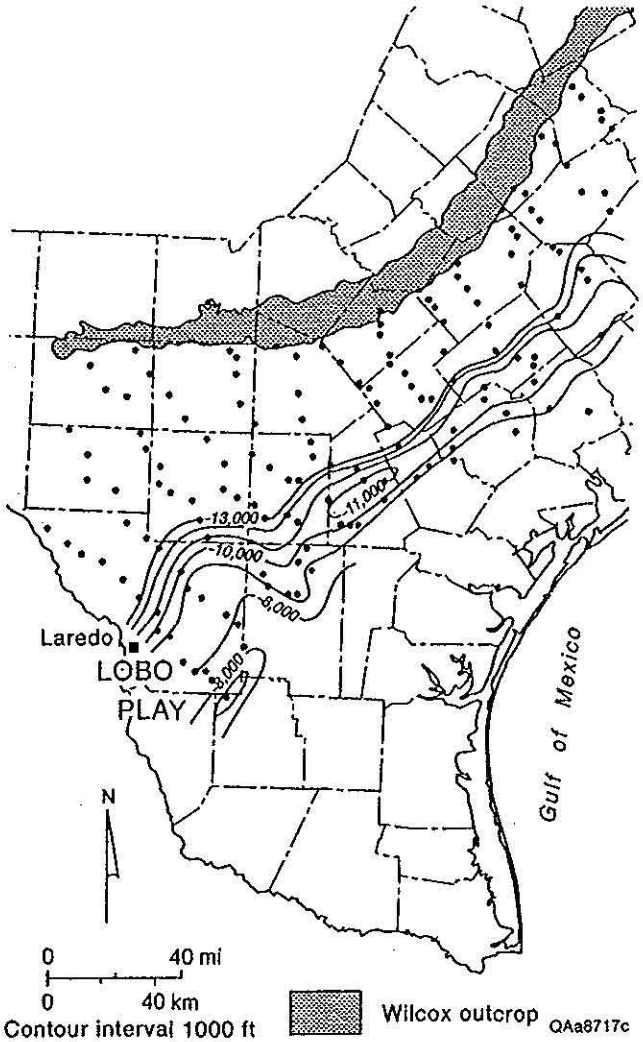

Figure 41. Depth to the operational top of geopressure along the Wilcox geothermal corridor, Texas Gulf Coast. These depths were determined primarily on the basis of shale resistivity (R_{sh}) versus depth plots (Ewing, 1986).

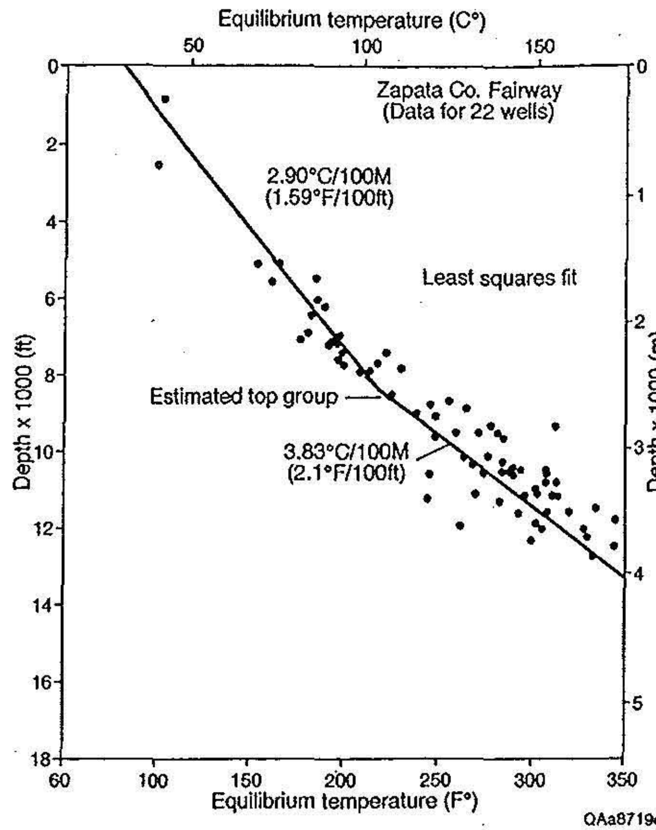

Figure 42. Temperatures and geothermal gradients for Zapata fairway, Burgos Rim domain (Ewing, 1986).

Summary of Lobo Domains

The setting of the Lobo play near the juncture of two major tectonic provinces—the Gulf Coast extensional province and the Cordilleran compressional province—resulted in development of at least three geographically separate and tectonically distinctive domains that have attributes that reflect the competing influence of thin-skinned extension, growth faults, salt tectonics, on one hand, and basement-involved compressional tectonics, folding, and tectonic uplift of highland areas on the other. These domains differ in fault trend and style, sand-body geometry, sandstone provenance, and their setting relative to evolving regional salt-tectonics structures. There are likely important influences on compartment size, sandstone and cement composition (and thus reservoir quality) and fluid attributes. The main way that these features were influenced by the overall setting was through tectonic control on the orientation (strike), slope angle (dip), width, and stability of shelf areas.

Identification of these Lobo geologic domains provided a framework for subdividing the Lobo play, documenting and comparing reservoir properties, and predicting sandstone geometry and composition patterns. Testing and verifying these domains requires mapping approaches and more extensive core and production analysis. Domain analysis provides several testable hypotheses for regional Lobo geology and production attributes.

Regional geologic domains are but one aspect of the geology of the Lobo play. Many attributes of Lobo reservoirs are likely to be controlled by regional patterns and local geologic circumstances that affect all domains equally, or that have effects that are not primarily governed by location within a domain. For example, reservoir rocks are at a wide range of depths in all three Lobo domains, and depth-related diagenetic changes, as well as pore pressure and stress effects, likely have a strong effect on reservoir behavior. Similarly, proximity of faults can have a profound influence on reservoir fractures and diagenesis that is not directly related to location in a domain (figs. 43, 44, and 45). Yet local variations (i.e., on a fault block or reservoir scale) in formation pressures, water chemistry, and gas chemistry are also likely to be linked to regional patterns, as has been demonstrated in other geologic settings in other basin (Kaiser and others, 1994). Possibly Lobo geologic domains will prove useful for subdividing subregional hydrochemical facies and formation pressure variations (for example) that may be useful for predicting production attributes such as well deliverability.

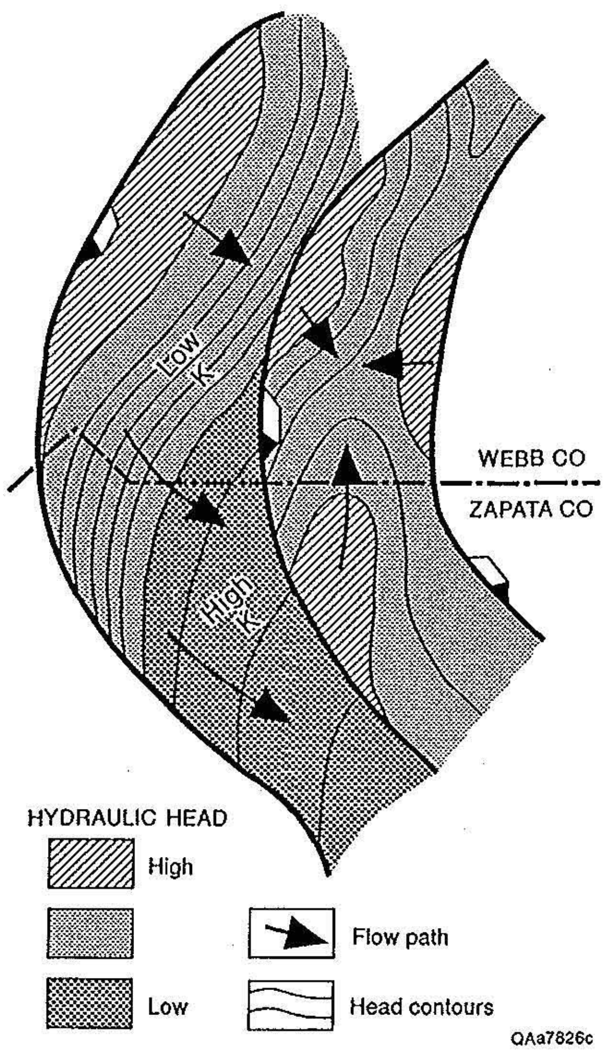

Figure 43. Conceptual regional map of formation pressures (potentiometric surface) in the Lobo trend. Such maps have the potential to identify faults and other permeability barriers, and pressure anomalies, which may represent isolated reservoir compartments. Areas of closely spaced head contours indicate 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.

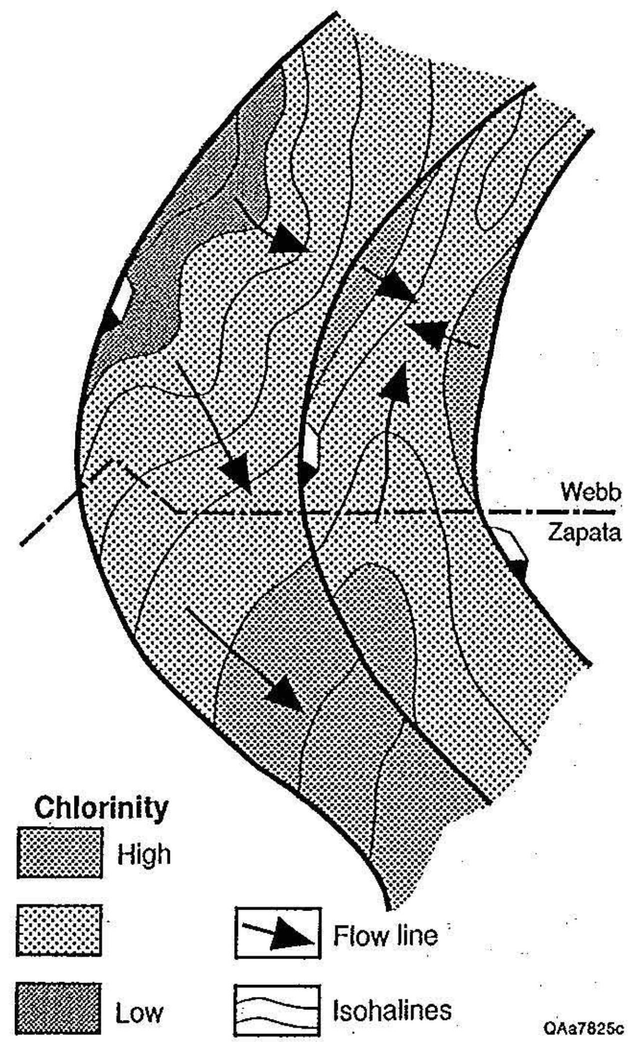

Figure 44. Conceptual regional map of chlorinity in the Lobo trend. Use of this mapping technique with formation-pressure mapping would be a potentially effective means of more clearly delineating regional fault trends in the Lobo area. Water flow can be both toward and away from areas of higher salinities, but it is always perpendicular to isohalines.

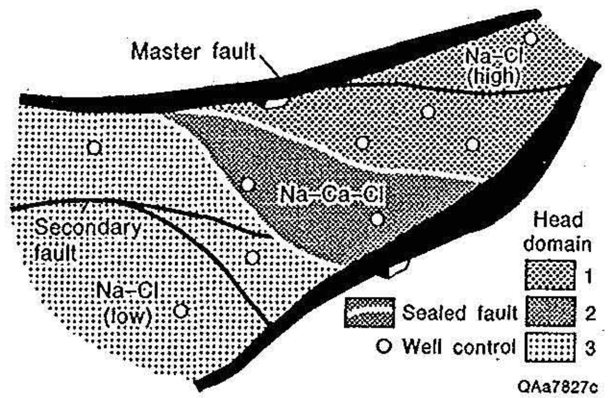

Figure 45. Conceptual subregional map illustrating the combined use of hydrochemical-facies and formation-pressure (head domains) data to locate reservoir compartments at the step-out scale in the Lobo trend.

Implications

Although extreme faulting hinders regional sandstone identification within the Lobo play, the tectonic setting of the play, and patterns in Lobo geologic attributes that can be recognized based on identification of domains within the play can help point to patterns in sandstone shape and trend, composition, and structural style, that can be used to refine local studies of the play. Some of the implications of this domain view of the Lobo trend are summarized in table 5.

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, of which the Wilcox Lobo represents one end member. In turn, the distribution and character of stratigraphic and structural patterns may be influenced by the area of the play in which they occur. These considerations led to the following conclusions.

Our study implies that from northeast to southwest across the Lobo play area, sandstones grade from dominantly strike-oriented, lobate bodies many times larger than fault compartments, to dominantly lenticular sandstones that have an important dip-oriented element. Structural compartments therefore are expected to be most prominent in the Cotulla domain, but to the south and west, mixed structural and stratigraphic compartments, and even purely stratigraphic compartments become more important. Although average sandstone composition is relatively uniform, an increasing proportion of unstable grains to the southwest in parts of the Central and much of the Burgos Rim domains could lead to lower preserved porosity and to more need for clay-sensitivity analysis. Fault patterns vary by domain; the recognition of basement and salt tectonic controls on fault patterns suggests approaches based on analysis of models and analogs that can lead to improved recognition of fault patterns.

Identification of Lobo domains is a first step toward establishing regional sandstone and other reservoir attribute patterns that can help guide site-specific work, such as picking drilling locations and evaluating completion intervals, which demands such large expenditures of time and technology. The need for such regional sandstone correlations is clear: such information can reduce uncertainties and guide site-specific work, and it is also critical as a basis for playwide comparisons to establish controls on productivity and to determine the size and location of the remaining gas resource. Such information helps increase development efficiency and production of a greater percentage of remaining gas in place.

Many aspects of the Lobo play remain uncertain because of widespread faulting that hinders conventional regional sandstone mapping. Identification of tectonically controlled domains cannot substitute for the information that such maps would provide. Nevertheless, as a tool to guide exploration and development strategy, as table 5 shows, it has revealed several testable hypotheses for the overall pattern of the Lobo play.

Acknowledgments

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Appendix A. Lobo Engineering and Production Characteristics

Engineering

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 8). 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 (fig. 46) and is high because of the abundance of clay in the Lobo sandstones. Water saturation ranges from 25 to 70 percent (table 8). 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 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

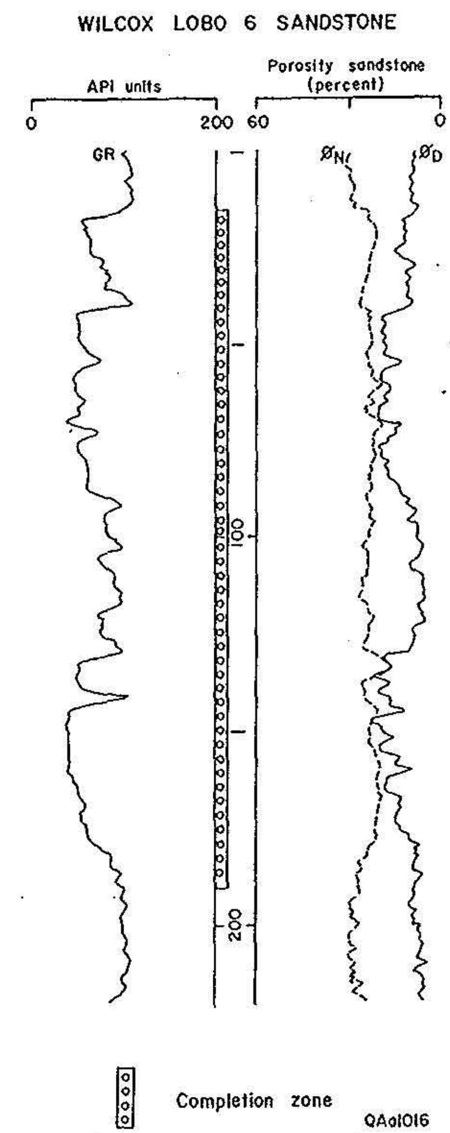

Figure 46. Porosity logs from a typical Wilcox Lobo well showing the Lobo 6 sandstone completion zone. From Berlinger and others (1988). Well identification and actual zone depth are not reported.

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.

Table 8. 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

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 8). 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. 47). Individual Lobo reservoirs display a variety of production trends, some steeply rising and others in decline (fig. 48). 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 9). 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. 49). In the middle of the range, however, two-thirds of the reservoirs account for two-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.

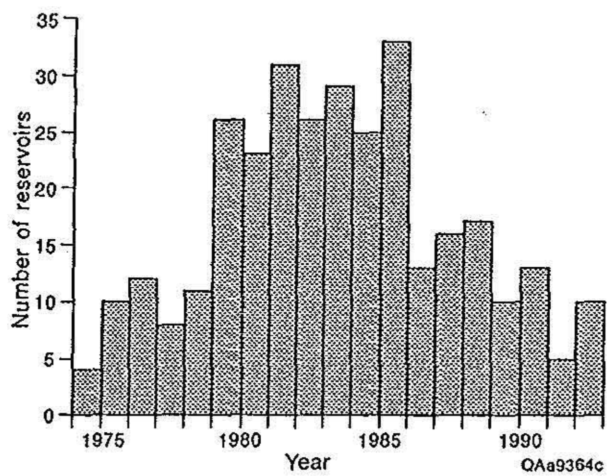

Figure 47. Number of new Lobo reservoirs discovered each year from 1974 to 1992.

Table 9. Wilcox Lobo cumulative production statistics through 1992 (in 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

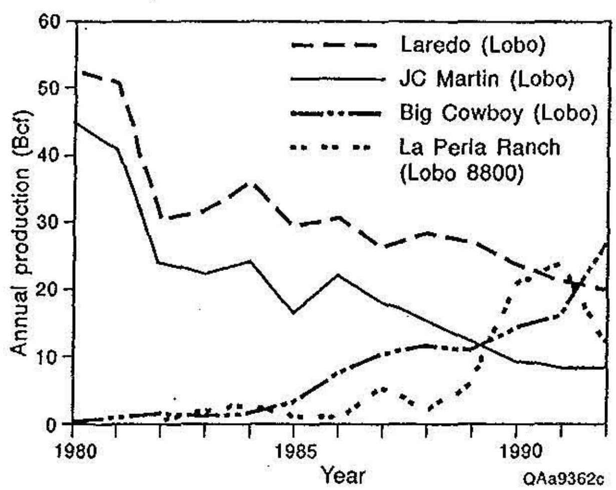

Figure 48. Production histories of selected Lobo reservoirs.

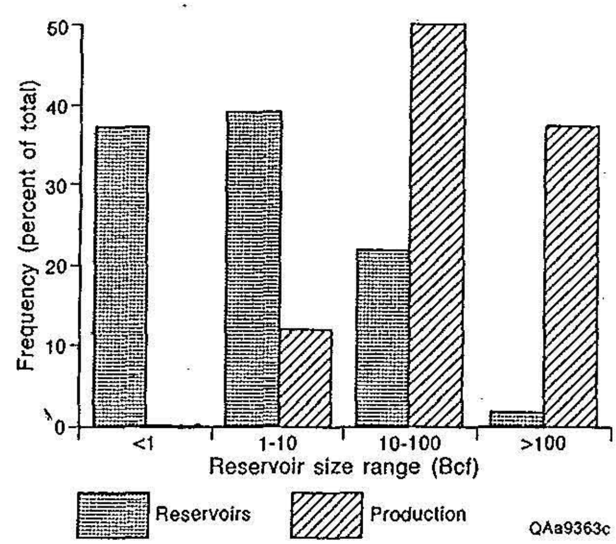

Figure 49. Distribution of Lobo reservoir size classes in terms of total Lobo gas production and reservoir frequency.

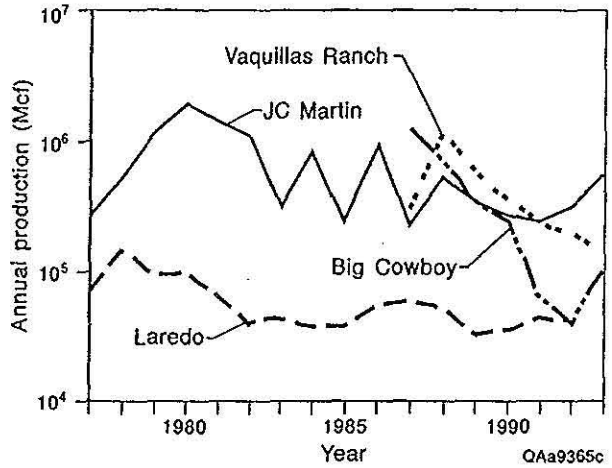

Figure 50. Production histories of selected Lobo wells.

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 9). Daily production rates also vary widely between about 100 and 50,000 Mcf/day. Finally, Lobo wells display differing production decline trends (fig. 50). Variabilities in well productivities reflect heterogeneities in reservoir compartment sizes and petrophysical properties.