STRUCTURAL STYLES OF THE WILCOX AND FRIO GROWTH-FAULT TRENDS IN TEXAS: Constraints on Geopressured Reservoirs

by Thomas E. Ewing

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1986

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by Thomas E. Ewing

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ABSTRACT

The wide variability in structural styles within the growth-faulted, geopressured trends of the Texas Gulf Coast is illustrated by detailed structural maps of selected areas of the Wilcox and Frio growth-fault trends and quantified by statistical analysis of fault compartment geometries. Structural variability is a key determinant of the size of geopressured aquifers in the deep subsurface.

Two major structural styles exist in the Wilcox trend. (1) In southeast and Central Texas, the trend consists of continuous, closely spaced faults that have little associated rollover despite moderate expansion of section; the fault plane flattens little with depth. Where the trend crosses the Houston Diapir Province, growth faults are localized by preexisting salt pillows; however, the salt diapirs pierced the growth-faulted horizons after the main phase of faulting, so that salt-related movement deforms the growth faults. (2) By contrast, in South Texas a narrow band of growth faults having high expansion and moderate rollover lies above and downdip of a ridge of deformed, overpressured shale but updip of a deep basin formed by withdrawal of overpressured shale. Large antithetic faults are associated with this band of faults.

Frio fault systems generally display greater rollover and wider spacing than do Wilcox fault systems; however, the Frio trend displays distinctive features in each study area. At Sarita in South Texas, shale mobilization produced shale ridges, one of which localized a low-angle growth fault. Shale mobilization at Corpus Christi produced a series of large growth faults, shale-cored domal anticlines, and shale-withdrawal basins, which become younger to the east. At Blessing, major growth faults show little progradation seaward. A major early-formed growth-fault system was deformed by later salt tectonism at Pleasant Bayou. At Port Arthur, low-displacement, long-lived faults formed on a sand-poor shelf margin contemporaneously with broad salt uplifts and basins. Most of the Frio growth faults, however, have a similar geometry, showing substantial rollover, expansion of section, and a moderate flattening of the fault zone with depth, possibly related to a deep décollement surface. Shale ridges are common but not ubiquitous. The local variability in style is related to the magnitude of Frio sedimentation and progradation and to the presence of thick salt or shale.

Data on the sizes and shapes of fault compartments in the Texas Gulf Coast growth-fault trends confirm substantial differences between the two fault systems. Frio compartments generally show less elongation and higher absolute curvature than do Wilcox compartments. The compartment areas in both trends are distributed exponentially (small compartments outnumber large ones). There are more very large compartments than the best-fit exponential model predicts, however. The observed distribution of fault compartment curvature is consistent with a simple trapezoidal model of their geometry.

Finding and developing a large geopressured aquifer require recognition of a favorable combination of sand-body geometry, reservoir quality, and fault compartment size and shape. In the Wilcox trend, reservoirs are predominantly dip-oriented sandstones of high-constructive deltaic origin. This geometry, together with the close spacing of faults and the characteristically low permeabilities, limits the size of geopressured reservoirs. The largest reservoirs in the Wilcox trend may be in areas between major fault trends or in salt- or shale-withdrawal basins. In the Frio trend, widely spaced faults and higher permeabilities are more favorable to reservoir development. Blocks showing dip reversal and salt- and shale-withdrawal basins were all found in the trend and are likely to contain large geopressured aquifers. Reservoir quality is the primary limitation.

Keywords: Gulf Coastal Plain, Texas, Tertiary, structural geology, clastic sediments, geopressure, faulting, salt tectonics, seismic surveys, geothermal energy

INTRODUCTION

The Tertiary Gulf Coast Basin of Texas, Louisiana, and northeastern Mexico contains abundant subsurface normal faults within a thick sedimentary sequence (fig. 1). These faults cause substantial expansion of down-thrown parts of the sequence, indicating that they developed during deposition; hence they are termed growth faults. Outside the areas of abundant salt diapirism, these faults

are oriented parallel to the regional strike of the basin and to the Cretaceous shelf margin. Their time of greatest movement is coincident with progradation of the shelf margin by large quantities of clastic sediment fed to the basin by large rivers (Winker, 1982; Winker and Edwards, 1983). As a result, they form discrete bands, or trends, which decrease in age to the east and south, reflecting the pro-

FIGURE 1. Growth-fault trends of the Texas part of the Gulf Coast Tertiary Basin; stratigraphic column.

gressive infilling of the Gulf of Mexico. These trends probably continue through the areas of salt diapirism, but they have been disrupted by the effects of salt mobilization. In Texas, three major growth-fault trends are recognized onshore: the Wilcox trend of the late Paleocene and early Eocene, the Vicksburg trend of the early Oligocene, and the Frio trend of the late Oligocene. Miocene and younger trends occupy successive belts on the continental shelf.

Regional studies conducted by the Bureau of Economic Geology assessed the presence of geopressured geothermal resources within the major growth-fault trends of the Texas Gulf Coast Basin (Bebout and others, 1978, 1982; Weise and others, 1981a, b). Because of the methods used, these studies only assessed the part of the rock column that had been extensively drilled during oil and gas exploration. To assess prospective areas that had been inadequately drilled and to define areas that might be productive, the different structural styles within the growth-fault trends should be understood. A regional synthesis also allows extrapolation of results from the detailed study of prospect areas to the entire trend.

Structural style and evolution can best be analyzed in areas having both dense, deep well control and seismic coverage. Seismic lines obtained by the Bureau of Economic Geology form two categories: (1) grids of

data around prospect areas having test well sites and (2) regional dip-oriented seismic reflection lines that provide representative coverage within the growth-fault trends. The prospect grids of the three identified geopressured geothermal prospect areas were previously analyzed and combined with well data (Winker and others, 1981); work on the Port Arthur dispersed gas prospect is reported here and elsewhere (Gregory and others, 1983). The regional seismic lines, however, have never been systematically studied, although one seismic line across the Vicksburg growth faults in South Texas was interpreted by Han (1982) in a study of the McAllen Ranch field and adjacent areas.

In this report, three study areas are defined within the Frio growth-fault trend: the Sarita, Corpus Christi, and Port Arthur areas. These areas, together with the Blessing and Pleasant Bayou prospects described by Winker and others (1983), span nearly the entire range of Frio depositional systems, as defined by Galloway and others (1982). Three areas in the Wilcox trend were studied: the Katy, Fostoria, and Zapata areas. Together with Winker and others' (1983) study of the Cuero area (De Witt County) and Edwards' (1980) brief description of faulting in Live Oak County, this work provides a comprehensive view of Wilcox structural styles and depositional systems.

===== WILCOX GROWTH-FAULT SYSTEM =====

The Wilcox trend, lying more or less adjacent to the Lower Cretaceous carbonate shelf margin, is the most landward major growth-fault (syndepositional listric normal fault) trend in the Texas Gulf Coast Basin. Major activity on the faults of this trend occurred in Paleocene and early Eocene time, during deposition of Wilcox Group deltaic sands and muds that prograded the shelf margin (Bebout and others, 1982;

Winker, 1982). The lower Wilcox (Paleocene) Rockdale delta system (Fisher and McGowen, 1967) advanced the shelf margin in East Texas; progression of the South Texas shelf margin by the Wilcox Rosita (Eocene) delta system followed (fig. 2; Edwards, 1982). Lower Wilcox sandstones in South Texas are also geopressured and growth faulted in the distinct Lobo growth-fault trend.

QA-1578

FIGURE 2. Location map showing study areas in the Wilcox growth-fault trend, Texas Gulf Coast, and their relation to the Rockdale and Rosita delta systems.

Katy Study Area

Most of Waller and Austin Counties and parts of Harris and Fort Bend Counties are included in the Katy study area in southeast Texas (fig. 3). Correlations within the Wilcox were extended from studies of the Colorado and Harris fairways (Bebout and others, 1982). More than 200 well logs were examined and correlated, and two regional dip-oriented seismic lines were interpreted. Examination of structure maps on file at the Railroad Commission of Texas improved the mapping of productive structures.

The Katy area lies in the northwestern part of the Houston Diapir Province (fig. 2). Two shallow piercement salt diapirs occur: Hockley salt dome in Harris County (salt at -200 ft [-60 m] as measured from sea level) and San Felipe, or Brookshire, salt dome in Waller and Austin Counties (salt at -2,600 ft [-780 m]; Halbouty, 1979). Both of these domes were the site of minor hydrocarbon production. Raccoon Bend field in north-eastern Austin County overlies a deep-seated salt diapir (salt at -11,004 ft [-3,301 m]).

This area has yielded significant quantities of oil and gas from the Yegua Formation at Raccoon Bend and Katy fields as well as from smaller fields such as Fulshear and Clodine in the southeastern corner of the area. The Wilcox yielded gas at Sealy, Orange Hill, and Katy fields. Little deep drilling has taken place; of the more than 200 wells examined, only about 95 reach the top of the Wilcox Group. Seismic lines were therefore essential in interpreting the deep structure of the area.

Stratigraphy

No borehole information is available on the sub-Wilcox stratigraphic units in the Katy area; however, seismic reflection data together with regional information allow some inferences. The lowest units defined on seismic sections are from Lower Cretaceous carbonates. These carbonates lie seaward of the major Sligo and Stuart City (Edwards) reef trends and are inferred to represent their basinal facies equivalents. Undifferentiated

marine Gulfian (Upper Cretaceous) and Midway (lower Paleocene) strata overlie these carbonates. Seismic sections indicate a sequence of prograding clinoforms, representing the seaward advance of the Wilcox shelf margin, in the upper Midway and basal Wilcox Groups.

The lower Wilcox Group is a sandstone-rich (more than 60 percent sandstone) clastic sequence deposited in the Rockdale delta system (Fisher and McGowen, 1967). Sandstone percentage in the upper part of the lower Wilcox remains high as far to the southeast as the unit was penetrated, suggesting that deltaic progradation continued far southeast of the Katy area. Seismic data indicate that the lower Wilcox Group ranges in thickness from 3,600 ft (1,080 m) to more than 6,000 ft (1,800 m) in the area.

The middle Wilcox Group is a sandstone-shale sequence, probably of deltaic origin, having less sandstone (generally 20 to 40 percent) than the units below and above. To the northwest, this unit becomes less distinct. The upper Wilcox Group is a sandstone-rich (40 to 75 percent) clastic sequence. It is part of a region of abundant sandstones in southeast Texas (mapped by Bebout and others, 1982) inferred to represent a delta system that succeeded the lower Wilcox Rockdale delta system. The combined middle and upper Wilcox Group ranges from 1,700 ft (510 m) to more than 5,000 ft (1,500 m) in thickness.

The overlying lower Claiborne Group consists of 1,500 to 2,000 ft (450 to 600 m) of neritic shale. Sandstones and siltstones of the Sparta and Queen City Formations are found northwest of Raccoon Bend but do not persist basinward. The Yegua Formation (upper Claiborne Group) consists of 1,500 to 2,000 ft (450 to 600 m) of sand and shale (10 to 60 percent sand). Sand-percent maps (not shown here) indicate that the northern half of the area was dominated by a fluvial regime with dip-oriented sandstones, which fed a strike-elongate system in the southern half of the area.

The Jackson Group overlies the Claiborne strata. Although mostly marine shale, the

FIGURE 3. Location map of Katy study area. Tobin grid numbers given in margins of all maps.

Jackson Group contains sandstones in the northwestern part of the area. The overlying Vicksburg Formation (lower Oligocene) is a sandstone-shale sequence in which minor fluvial axes in Austin and Waller Counties merge southward to form a strike-oriented deltaic sandstone trend (Gregory, 1966). The overlying Catahoula and younger strata are nonmarine fluvial-streamplain sediments.

Velocity structure of these sedimentary units was derived from velocity analyses made during routine processing of the seismic lines. In general, the velocity structure of the Katy area is similar to that of the Cuero area to the southwest (Winker and others, 1983). However, in the Katy area, the Sparta horizon yields a strong reflector that masks the distinctiveness of the top Wilcox reflector. The Sparta reflector is probably related to constructive interference, as no large velocity break exists. Velocities in the Wilcox vary across the area; lower velocities are in the basinward areas, as in the Cuero area. This velocity decrease is probably related to a combination of decrease in the amount of sand and a shallower first occurrence of geopressure. Although no detailed study of the distribution of geopressure has been made, data presented by Bebout and others (1982) indicate that the lower Wilcox interval is geopressed in the central and southeastern parts of the Katy area. The upper Wilcox is hydropressed throughout most of the Katy area.

Structural Development

Detailed well log correlation and seismic interpretation were combined to produce structure maps on the Vicksburg, Yegua, and upper Wilcox horizons; isopach maps of the Vicksburg, Jackson, Claiborne, and upper and middle Wilcox units; and true-depth structure sections paralleling the seismic lines and crossing San Felipe salt dome. Three phases of structural development are indicated: a Mesozoic salt-pillow phase; a Wilcox phase of growth faulting associated with shelf-margin progradation; and a post-Wilcox phase of piercement salt diapirs.

Evidence of the nature and scope of pre-Wilcox tectonics in the area is confined to the seismic data. On dip-oriented seismic lines, as shown on the cross section in figure 4, a thinning of the Gulfian strata is visible near the later-formed withdrawal basins around the salt domes. This suggests that an early-formed, broad salt-cored uplift was present at and updip of each of the two domes. Such uplifts may have been underlain by non-diapiric salt pillows similar to those in the East Texas Basin (Seni and Jackson, 1983). The Raccoon Bend structure, as well as the Sealy structure to the southwest, may be similar in geologic history to the Brenham line of salt domes in Washington and Burleson Counties to the northwest, which appears to have a Cretaceous diapiric history.

The former salt pillows at the San Felipe and Hockley domes and their related salt-withdrawal basins lie on trend with two large oil-productive domal structures, Conroe and Tomball, to the northeast (Ewing, in preparation). Conroe salt dome is the site of a marked gravity low (Hammer, 1983, p. 222). These large features are probably salt pillows that failed to develop into piercement salt domes after progradation of the Wilcox shelf margin. This northeast-trending alignment of pillows may have developed along an early-formed salt-cored ridge seaward of and parallel to the Lower Cretaceous carbonate shelf margin.

The Wilcox phase of tectonic activity is shown on the upper Wilcox isopach map (fig. 5). Several large growth faults trend southwest-northeast across the San Felipe and Hockley salt dome areas. These faults were previously mapped in the Orange Hill field. The base of the lower Wilcox is not well defined basinward of these faults; however, faint downlapping reflectors in one seismic line suggest that the lower Wilcox section has undergone at least a twofold expansion across this fault system. Upper and middle Wilcox growth on these faults is also considerable; expansion indices (down-thrown thickness/upthrown thickness) are 1.3 to 1.6 on each fault (fig. 4). The faults flatten downward somewhat, suggesting a

FIGURE 4. Structure section A-A', Austin and Fort Bend Counties; line of section shown in figure 3. Note the thinning of Gulfian and Midway strata beneath the San Felipe withdrawal basin.

décollement plane above the Lower Cretaceous carbonates; however, the quality of the seismic data is insufficient to demonstrate this fully. The lower and middle Wilcox units in the fault zone show dip reversal (landward dip). Another belt of large growth faults is found in the southeastern corner of the area and includes the Fulshear and Clodine faults. The faults were active during middle and upper Wilcox deposition; expansion indices ranged from 1.7 to greater than 2.5. These faults may have a shallower dip and less curvature than do the lower Wilcox faults.

Salt tectonism was subdued during Wilcox deposition. The anomalous thickening of the Wilcox strata landward of the Orange Hill fault near San Felipe salt dome suggests that a withdrawal basin had developed during Wilcox deposition. However, much of the development of this basin was masked by large-displacement growth faulting. Present data indicate that the salt stocks at San Felipe and Hockley salt domes were probably absent during the main phase of growth faulting, as at Danbury salt dome in the Brazoria fairway of the Frio trend (Winker and others, 1983). The Sealy and Raccoon Bend structures were persistent areas of less sediment accumulation during Wilcox deposition, suggesting that these salt domes, although they failed to diapirically intrude the massive clastic influx of the Wilcox, continued to be uplifted.

The identification of large-displacement growth faults of early to middle Wilcox age (the Orange Hill system) and of middle to late Wilcox age (the Fulshear-Clodine system) is consistent with the stratigraphic record of substantial early Wilcox (Rockdale) and possible late Wilcox deltaic shelf-margin progradation. These deltaic systems prograded from northwest to southeast, burying the salt pillows in a mass of unstable clastic sediment. In the wake of the shelf-margin progradation, the growth faults stabilized and salt stocks grew from the pillows.

In contrast to the Cuero and Live Oak areas (Edwards, 1980; Winker and others, 1983), the first Wilcox-age growth faults do not occur immediately downdip from the

FIGURE 5. Isopach map of upper and middle Wilcox strata, Katy study area.

Cretaceous reef trend but rather 20 mi (32 km) or more basinward. Most previous workers assumed that the first progradation of the Wilcox sand over thick basinal shales started growth faulting (Winker and Edwards, 1983); however, the history of faulting appears to have been more complex in the Katy area. The location of the Orange Hill fault system may have been controlled by the line of nondiapiric salt pillows, much as other growth-fault systems are controlled by shale ridges (Bruce, 1973). Stability updip of the pillows may have been promoted by the buttressing effect of the pillows, despite the presence of 6,000 ft (1,800 m) of Gulfian shale and marl. Instability was concentrated over the pillows, and a décollement surface developed on their basinward slopes (fig. 6).

After Wilcox time, salt tectonism became the dominant feature of the area. The two piercement salt domes, each associated with a deep crescent-shaped salt-withdrawal basin, pierced and deformed the Wilcox (fig. 7) and Claiborne strata. Both domes are located along the Orange Hill fault system and pierce the major fault planes. The associated basins lie updip from the salt stocks; together the deep basin and the stock outline the original pillow shape. The Katy domal anticline originated after Wilcox time as a residual high between the two withdrawal basins and the area of continuing growth faulting to the southeast. Alternatively, this high may be a sediment-cored turtle structure formed by infilling of a pre-Wilcox interpillow withdrawal basin. The Sealy and Raccoon Bend structures continued to be slightly uplifted during Claiborne time, testifying to the continued buoyancy of their underlying salt masses.

Activity during Jackson and Vicksburg time was largely confined to continued uplift of the salt stocks, slight uplift of the Raccoon Bend and Sealy structures, and sinking of the withdrawal basins (fig. 8). After Vicksburg deposition, the Claiborne and Jackson strata were pushed up and overturned along the western flank of San Felipe salt dome (fig. 9) and developed a local unconformity upon which Frio/Catahoula sediments were deposited (Halbouty and Hardin, 1954).

Multiple cap rocks on Hockley salt dome (Canada, 1962) suggest an episodic uprise of the salt stock there as well.

Post-Vicksburg structural activity continued the Jackson and Vicksburg activity patterns (fig. 10). Growth of the San Felipe salt dome apparently ceased in Frio time because it is buried by Frio and younger sediments. Hockley salt dome, however, continued to pierce and deform sediments as young as Pleistocene time. Loading of the crust by the large Frio and Miocene depocenters near Houston tilted the entire region to the southeast.

Structural Constraints on the Occurrence of Geopressured Reservoirs

Geopressured sandstone reservoirs are found downdip of the Orange Hill fault system in the Wilcox Group. Wilcox sandstones updip of this fault system have not been tested but are probably not highly geopressured because of aquifer continuity updip. The growth-fault trends of the Wilcox in the Katy area (fig. 5) are similar to those to the southwest that have yielded large quantities of geopressured natural gas. In Austin and Waller Counties, these fault trends have been deformed by salt tectonism, but gas-productive reservoirs should still exist; the deep potential of the area has not been adequately determined (Ewing, 1983).

Although the lower Wilcox has been penetrated by only a few wells in the Katy area, those penetrations, along with regional considerations, suggest that the typical geopressured reservoirs may be distributary-channel and related delta-front sandstones similar to those in the Cuero area (fig. 2; Winker and others, 1983). Fault-block geometry within the fault systems is expected to be similar to that at Cuero: highly elongate with limited dip extent, a combination that limits aquifer volumes. The area between the two fault systems, however, has a much broader dip extent and may contain larger aquifer volumes. Large geopressured aquifers may exist near Katy field and south of San Felipe salt dome.

Low permeabilities in Wilcox sandstones in the Harris and Colorado fairways (Bebout

QA 431

FIGURE 6. Schematic palinspastic sections across San Felipe area showing sequence of structural development.

EXPLANATION

FIGURE 7. Structure map contoured on top of Wilcox strata, Katy study area.

QA436

EXPLANATION

Fault

Expansion index of fault

Contour interval = 100 ft

QA437

FIGURE 8. Isopach map of Vicksburg and Jackson strata, Katy study area.

FIGURE 9. Structure section C-C' across San Felipe dome, Austin, Waller, and Fort Bend Counties; line of section is shown in figure 3.

and others, 1982) inhibit the flow rates necessary for geopressed geothermal energy production. Low permeabilities reduce the quality of geopressed geothermal reservoirs in the sand-rich Wilcox sequence in the Katy area.

Fostoria Dip Section

A dip-oriented section across the Wilcox growth-fault trend in western Liberty County was constructed using a regional seismic line and all available well information. The line (fig. 11) extends from southern San Jacinto County across the Fostoria fault block southward into the rim syncline of North Dayton salt dome. The line lies on the northern flank of the Houston Diapir Province (fig. 2) and within the Harris geopressed geothermal fairway (Bebout and others, 1982).

In addition to the lower Wilcox gas produced at Fostoria field, significant amounts of gas were produced from the

Wilcox in Cleveland and Lick Branch fields; Yegua oil and gas also were produced in Quinn and Splendora fields. Many wells penetrate the upper Wilcox in the updip part of the area, but no wells here completely penetrate the lower Wilcox.

Stratigraphy

Neither the sub-Wilcox strata nor the marginal-marine base of the lower Wilcox have been drilled. The Fostoria area is about 20 mi (32 km) basinward of the Lower Cretaceous reef trend. Although the area lies downdip of some mapped faults of the Wilcox growth-fault trend, the deep Cretaceous yields some distinctive reflections on the seismic line north of Fostoria. Prograding clinoforms in the Midway interval are not observed on the seismic section; the base of the Wilcox is picked at a change in reflection character from less-continuous reflectors in the fluvial-deltaic

EXPLANATION

Fault

Datum: top of Vicksburg

Contour interval = 100 ft

QA434

FIGURE 10. Structure map contoured on top of Vicksburg Formation, Katy study area.

FIGURE 11. Map of Fostoria area, Liberty and Montgomery Counties, showing approximate locations of dip section and oil and gas production.

Wilcox to more-continuous reflectors in the Midway or Gulfian section.

The lower Wilcox Group is a sand-rich clastic sequence (fig. 12) that forms part of the Rockdale delta system (fig. 2; Fisher and McGowen, 1967). Sand percentage is high in the lower Wilcox to the downdip limit of well control; the final deltaic shelf margin is therefore inferred to lie basinward of this limit (south of Fostoria field). The presence of continuous reflections in the deep basin northwest of North Dayton salt dome suggests that the interval may have passed into a marginal-marine to marine facies. Lower Wilcox strata thickness is unknown but probably ranges from 4,000 ft (1,200 m) updip to perhaps as much as 8,000 ft (2,400 m) downdip.

The middle Wilcox Group is a slightly less sand-rich sequence, probably of deltaic origin. It is less distinctive here than farther to the west and southwest (as in the Katy or Cuero areas). The upper Wilcox Group is a sand-rich clastic sequence that forms part of the regional sandstone trend in southeast Texas mapped by Bebout and others (1982). Thickness of the combined upper and middle Wilcox Group ranges from 2,400 ft (720 m) to more than 7,000 ft (2,100 m).

The stratigraphic sequence above the Wilcox is basically the same as that in the Katy area. Strong continuous seismic reflectors are in the lower Claiborne Group, perhaps near the Sparta horizon, and in the Jackson Group marine strata above the Yegua deltaic(?) sequence. A thin interval of Vicksburg strata, overlain by the Catahoula Formation and by Neogene non-marine strata, occurs in the downdip part of the section.

Seismic-generated velocity analyses were used for time-depth conversion of the seismic data. The velocity structure in the Fostoria line, as in the Katy and Cuero areas, shows a downdip decrease in the Wilcox interval velocity. This decrease is most marked downdip of Wilcox penetrations and may reflect either a decrease in sand content or an increase in the degree of overpressuring. The top of geopressure rises downsection from within the lower Wilcox interval into the

middle Wilcox; the location of geopressure in the southern part of the line is unknown.

Structural Development

The Fostoria area has two distinct phases of structural development: one of Wilcox age and the other of post-Claiborne age (fig. 13). The deeper structure consists of four growth faults and a deep basin. The two updip faults expand the lower Wilcox section substantially but show only slight expansion of younger units. They have little associated rollover and flatten only slightly with depth, similar to the Wilcox trend at Cuero (Winker and others, 1983). The two downdip faults formed on the northern flank of a deep basin. They show large expansion of the upper and middle Wilcox sequence (as interpreted from seismic data) and continued to move through Claiborne time. The faults appear to become parallel to seismic reflectors in the lower Wilcox interval, suggesting that they may flatten into a detachment surface near the base of the lower Wilcox. The deep basin shows strong reflections down to 28,000 ft (8,400 m), but the age of this sediment is uncertain. Much of the basin, however, is filled with Wilcox-age rocks. This deep basin stopped subsiding at about the end of the Wilcox; Claiborne and Jackson strata are uniform in thickness across the section.

Post-Claiborne strata dip generally basinward, except that Oligocene (Catahoula or Frio) and Neogene strata markedly thicken into the rim syncline surrounding North Dayton salt dome. This thickening indicates that, although preceded by substantial Wilcox and Yegua sand deposition, the North Dayton salt dome became a piercement diapir during Oligocene time.

The deep Wilcox basin disclosed by the seismic data may, because of its location relative to North Dayton salt dome, represent a primary peripheral sink related to salt pillows beneath Fostoria and North Dayton fields. The form of the structural high underlying the growth faults at Fostoria field (strengthened by the upturned deep reflector in Cretaceous strata) suggests the presence of a pillow. A gravity low also underlies the Cleveland field east of the line (Hammer,

FIGURE 12. Structural cross section of the Fostoria area.

1983). The flexural appearance of the Claiborne sequence near well 9 (fig. 13) is thus due to an incomplete turtle structure. Some of the deep-basin reflectors might represent an intraslope basin developed before progradation of the Wilcox shelf margin.

Structural Constraints on the Occurrence of Geopressed Reservoirs

Geopressed sandstone reservoirs appear to be sparse in the Fostoria area. The lower Wilcox deltaic sand sequence is sand rich; geopressure occurs in the sequence

only at great depth. However, neither the deeper parts nor the downdip extension of the sequence have been tested, and more significant overpressures may occur there.

The part of the Wilcox that has been drilled is dominated by hydro pressured fluvial or distributary-channel sand bodies, which are expected to be low-volume, dip-oriented reservoirs such as those at Cuero (Winker and others, 1983). However, if these sand bodies occur in a geopressed, unfaulted deep basin, they could be significant reservoirs. The basal and downdip parts of the lower Wilcox should contain more continuous, possibly geopressed sands of marginal-marine (delta-front and strand-plain) origin; these constitute a significant but untested hydrocarbon and geothermal play. As in the Katy area, the Fostoria deep Wilcox sandstones may have low permeabilities.

Zapata Study Area

The Zapata study area includes most of Zapata County, the western edge of Jim Hogg County, and a small part of Starr County (fig. 14). The area lies within the Zapata geopressure fairway described by Bebout and others (1982). Well log correlations used in the previous study were checked and extended to all available wells in the area; proprietary seismic lines also were examined.

The Zapata area lies at the western margin of the Tertiary Rio Grande Embayment and contains complex structures associated with upper Wilcox shelf-margin progradation of the Zapata delta of the Rosita delta system (fig. 2; Edwards, 1982). In the western half of the area, structures associated with the lower Wilcox Lobo trend occur, as do gentle anticlines probably related to Laramide deformation.

Stratigraphy

Rock units older than Late Cretaceous have not been drilled in the Zapata area. Proprietary seismic lines show the presence of Jurassic salt that forms low-amplitude pillows and shallow withdrawal basins overlying a fairly flat basement surface. There are

FIGURE 13. True-depth interpreted section of Fostoria area. Numbers at top correspond to well numbers in figure 12.

FIGURE 14. Location map of Zapata study area.

salt diapirs in the area; the nearest diapirs are to the north and northeast (Pescadito in Webb County and Piedras Pintas in Duval County). Overlying the salt are high-amplitude reflectors representing a basinal carbonate sequence, which thickens northwestward into Upper Jurassic and Lower Cretaceous carbonates and related clastics. The basinal carbonates appear to thin markedly within 40 to 60 mi (60 to 80 km) basinward of the Lower Cretaceous reef trend; salt in the Zapata area lay under a thin sediment cover (0.6 mi [1 km] or so) during the middle Cretaceous. Thick Upper Cretaceous strata in the area consist of shale and marl, including the basinal (Mendez) equivalents of the San Miguel and Olmos deltas of southwest Texas and northeast Mexico and the Difunta Group deltas of Mexico.

Basal Wilcox sandstones, known as the Lobo sands, occur in the northwestern part of the Zapata area. Limited information suggests that they formed in a strike-fed sand system related to the Cotulla barrier-bar/strandplain system described by Fisher and McGowen (1967). The basal Wilcox is separated from the rest of the Wilcox Group by an angular unconformity in Webb and Zapata Counties, Texas, and in adjacent Mexico.

The upper Wilcox is a sand-rich progradational clastic unit, described by Edwards (1982) as the Zapata delta complex of the Rosita delta system (fig. 2). Updip, in the western part of the area, it is thin (less than 1,500 ft [450 m]) but thickens markedly to 8,000 ft (2,400 m) over a series of growth faults. Sand content decreases downdip, but the final seaward extent of shallow-water sand deposition is unknown.

The overlying Eocene units consist of strike-fed barrier-bar/strandplain sandstones and related shallow-marine shales of the Queen City (Guevara and Garcia, 1972) and Yegua (Fisher, 1969) Formations and the Jackson Group (Fisher and others, 1969). Yegua and Jackson units are exposed throughout most of the study area.

Velocity information from two wells in the main growth-fault trend shows a fairly constant interval velocity of 10,000 to

11,000 ft (3,000 to 3,300 m) per second below about 2,000 ft (600 m). Available information on seismic velocity is inadequate to show any decrease in interval velocity basinward. The top of geopressure lies in the middle Wilcox west of the growth-fault trend and rises above the top of the Wilcox within and east of the trend (Bebout and others, 1982).

Structural Development

Three major structural trends are found in the Zapata area (fig. 14): the basal Wilcox Lobo trend in the northwest; the upper Wilcox growth-fault trend in the east; and the gentle anticlinal folds in the west, which affect strata as young as the outcropping Yegua.

The basal Wilcox Lobo sandstones of the Zapata area are complexly faulted. Faults in this area appear to be listric normal faults that flatten into Midway or Upper Cretaceous shales at shallow depth. Faulted and folded basal Wilcox strata are unconformably overlain by unfaulted strata that dip basinward; the relation is shown on section A-A' (fig. 15A).

The upper Wilcox growth-fault trend extends north-south through eastern Zapata County (fig. 16). Where it is best known, the upper Wilcox consists of two to four major growth faults, commonly having more than threefold expansion of section (Bebout and others, 1982). This expansion, coupled with abundant antithetic faulting, makes regional structure mapping below the top of the Wilcox difficult. Substantial dip reversal occurs in the narrow, complex fault compartments between major faults (fig. 15). This narrow band of growth faults lies over and on the downdip side of a shale ridge, distinguished on seismic sections by chaotic reflections. Downdip of this shale ridge lies a deep synclinal basin filled with Wilcox and lower Claiborne sediments to depths of nearly 20,000 ft (6,000 m); another shale ridge lies east of this basin. Locally, large antithetic faults have formed on the downdip side of the shale ridge, producing large, deep traps such as that at Fandango field.

FIGURE 15. True-depth sections of Zapata study area. (A) Section A-A' through Lobo trend and Fandango structure. (B) Section D-D' through North Falcon Lake field. (C) Section F-F' across Cinco de Mayo anticline.

FIGURE 16. Structure map contoured on top of Wilcox strata, Zapata study area.

FIGURE 17. Dip cross sections of Fandango field, restored to its appearance in middle and late Wilcox time.

Reconstruction of a section at Fandango field (fig. 17) shows that the shale ridge, the growth-fault system with antithetic faulting, and the deep basin developed concurrently during upper Wilcox deposition. The shale ridge was apparently passive, although upward forcing may have helped to form the large antithetic fault near its crest in latest Wilcox time. Very thick sediment, inferred to be mobile shale, was forced out of the area below the deep basin, either into the updip shale ridge or, more likely, into the next shale ridge to the east. The deep basin is inferred to be a linear shale-withdrawal basin related to the formation of shale ridges.

Broad, plunging anticlines occur updip of and within the upper Wilcox growth-fault trend; they are best expressed at the lower Claiborne (base of the Yegua) horizon (fig. 18). Two anticlines, the Cinco de Mayo and the Lopeno, are mapped in outcrop (Barnes, 1976). Relief on the Cinco de Mayo anticline (fig. 15C) decreases from the top of the Lobo unconformity to the top of the Wilcox; low relief is nearly constant to the surface. These folds may be compressional, related to the open Tamaulipas folds, such as the Sierra Picachos anticline to the west, and to the low-amplitude foldbelt developed to the northwest in Maverick and Val Verde Counties, Texas, and adjacent Coahuila (Chittim, Del Rio, and Trevino anticlines) (Ewing, in preparation). The anticline may have been developed either by deformation of either Upper Cretaceous shale or Mesozoic salt or by basement warping. Post-Wilcox deformation may be related to compaction or to continued movement of incompetent sediments.

Structural Constraints on the Occurrence of Geopressured Reservoirs

Geopressured sandstone reservoirs are expected in two structural locations: within the narrow growth-fault belt and downdip in the deep shale-withdrawal basin. Reservoirs within the growth-fault belt are expected to be complexly faulted and limited in dip extent; hence, reservoir volumes in deltaic sandstones should be limited. However, strike-oriented sandstones within the trend,

such as the first Hinnant in the Northeast Thompsonville field (Morton and others, 1983), may have significant volume.

Sandstone reservoirs downdip of the fault trend, either near the large antithetic faults or in the deep basin, may be less faulted and hence have larger reservoir volumes. The critical control on sandstone distribution is the location of the final shelf margin established by the Zapata delta. Well control is nearly nonexistent; however, high-continuity seismic reflectors in and seaward of the basin are more characteristic of shelf-slope shale sequences than of deltaic sand sequences. Lack of permeable reservoir rocks may therefore limit geopressured reservoirs in this area.

Discussion

Three areas of contrasting structural style exist within the Wilcox growth-fault trend of the Texas Gulf Coast. One style is typical of the Cuero study area (Winker and others, 1983) and, modified by salt tectonics, of Katy and Fostoria. This style displays several fairly straight growth faults that show little flattening with depth and that bound highly elongate fault compartments. Expansion across the faults is moderate (indices of 2 to 3), but rollover, except in the most basinward faults, is minor. Salt, where diapirically active, pierces the growth-fault trend after the main phase of growth faulting. Older salt pillows, however, localize the growth-fault trend. A similar style occurs in Live Oak County (Edwards, 1980) and probably extends eastward into Louisiana. Another structural style, typical of the Zapata area, consists of a narrow belt of growth faults having great expansion and related antithetic faults. This style is localized on a linear shale ridge updip of a deep shale-withdrawal basin. A similar style extends northeast into Duval County and possibly into the South Chapa area of Live Oak County. This trend lies east of the lower Wilcox Lobo trend of highly listric faulting within a basal Wilcox sandstone sequence.

The South Texas Wilcox structural style appears to require more shale mobility than does the Cuero style. This may result from the

FIGURE 18. Structure map contoured on base of Yegua Formation, Zapata study area.

closeness of South Texas to the Sierra Madre, which was undergoing Laramide deformation during Wilcox deposition. Thick Upper Cretaceous and Paleocene shales (the Mendez and equivalents) fill a foredeep basin in northeastern Mexico and may extend into South Texas. The intra-Wilcox unconformity in the Lobo area and the gentle anticlines in Zapata County also indicate more structural activity in South Texas, which might have helped to create a concentrated belt of higher magnitude sliding near the Eocene shelf margin. The Cuero style, in contrast, shows little mobilization of the underlying shales; in fact, Wilcox faults may pass through Lower Cretaceous strata into Jurassic strata or into salt.

Exploration for geopressured gas resources is active along the entire Wilcox

growth-fault trend. Currently active exploration frontiers are the Fandango-type antithetic structures in South Texas and the deep lower Wilcox in Central and southeast Texas. The base of the lower Wilcox is sparsely drilled in most of southeast Texas but has much potential to produce from marginal-marine sandstones.

Most geopressured reservoirs in the Wilcox trend are deltaic (except for the Lobo). The trend largely consists of highly elongate fault compartments having less than 3 mi (5 km) of downdip extent; hence, reservoir sizes are limited. The largest reservoirs may be found in areas between major growth-fault trends, such as the deep shale-withdrawal basin in South Texas or the inter-fault parts of the Katy and Fostoria areas. Permeabilities in both of these areas, unfortunately, are poor (Bebout and others, 1982).

FRIO GROWTH-FAULT SYSTEM

The Frio growth-fault system (or Frio fault zone) lies just landward of the present coastline of the Texas Gulf Coast and occupies a belt some 40 mi (60 km) wide. Because of its large amounts and commonly favorable quality of sandstone, the Frio system is the one of greatest potential for geopressured resources. The faults formed contemporaneously with the progradation of the late Oligocene shelf margin by major deltaic and barrier-bar/strandplain systems (Galloway and others, 1982; fig. 19). Growth faults in the Houston delta system and the Buna system formed in an area of thick diapiric salt.

Two study areas at Corpus Christi and Port Arthur are described in this report. They lie within the Frio growth-fault and geopressure trend (Bebout and others, 1978). In addition, a regional line along the Kleberg-Kenedy county line is interpreted and related to the geology of the Sarita prospect area as defined by Weise and others (1981a). These areas, together with the Blessing and Pleasant Bayou prospects described by

Winker and others (1983), span nearly the entire range of Frio depositional systems (fig. 19).

Corpus Christi Study Area

The Corpus Christi study area (fig. 20) coincides with the Corpus Christi fairway studied by Weise and others (1981a), who established a series of 11 electric log correlation markers, CC-1 through CC-11, throughout the area. For the present study, their well log correlations were confirmed and extended; 600 well logs were examined. Two seismic lines were acquired, one in central Nueces County and the other in Nueces Bay. Combining dense well control with dip-oriented seismic lines allows reconstruction of a fairly detailed structural and depositional history.

The Corpus Christi study area lies within the southern part of the Greta-Carancahua barrier-bar/strandplain depositional system of the Frio Formation, immediately north of the northern margin of

FIGURE 19. Map of depositional systems of the Frio Formation showing locations of Frio geopressured trend study areas (from Galloway and others, 1982).

FIGURE 20. Location map of sections and wells used, Corpus Christi study area. The area covers most of the Corpus Christi fairway discussed by Weise and others (1981a). Names of major shale-cored domes are shown.

the Norias delta system (fig. 19). Most of the Frio sandstones represent strike-fed barrier-bar and strandplain sand bodies within the system. The sand system in this area prograded eastward from the lowermost Frio ("Frio-Vicksburg") of the Vicksburg fault zone fields of western Nueces County to the upper Frio near the present-day shoreline. This progradation, first reported by Boyd and Dyer (1964), apparently kept pace with the rapid eastward progradation of the Norias delta to the south of the area. In contrast, the main Greta/Carancahua sand system northeast of Corpus Christi appears to have prograded only slightly during Frio time, forming thick composite sandstones (Galloway and others, 1982).

Little detailed structural information on the Corpus Christi area has been published. Several of the shallow oil fields discovered early in the area were the subject of field studies. Maps of major fields were obtained from the files of the Railroad Commission of Texas to improve the rendering of the producing structures.

Stratigraphy

The Frio Formation in the study area ranges from 3,000 ft (900 m) to more than 8,000 ft (2,400 m) thick. The base of the Frio interval, or the top of the Vicksburg Formation, is arbitrarily taken at the occurrence of *Textularia warreni* in wells having paleontological data and at correlative horizons in other wells (fig. 21). Vicksburg strata have not generally been reached southeast of the western major growth fault in the study area. The top of the Frio is defined as the top of the sandstone-rich sequence overlain by the Anahuac marine shale (Holcomb, 1964). The Frio, as defined, includes sandstones of the *Marginulina* and *Heterostegina* biozones, which pass downdip into Anahuac shale.

Logs from deep geopressed wells show an overall separation into two sections. The upper section consists of thick, clean, upward-coarsening sandstones or composite sandstones, which represent the prograding barrier bars. In landward positions, these sandstones thin and grade into limy and

FIGURE 21. Stratigraphic diagram of Frio and related units, Corpus Christi study area, showing electric log correlation markers used in this study (CC-1 through CC-11). Approximate benthic foraminiferal correlations are shown; the occurrence of fossils, however, rise considerably in the section as one proceeds basinward (M. B. Edwards, personal communication, 1981).

lignite-bearing shales of lagoonal to paludal origin. Below a rather sharp horizon, the individual sand bodies are thicker but more shaly and are interbedded with thick marine shales. These sandstones may be traced updip across a major growth fault into sands of the upper section. Geopressure generally occurs at the base of the sandstone-rich upper section; the thicker, shaly sandstones are the geopressed geothermal target. The stratigraphic position of the transition between upper and lower sections varies from lower Frio (CC-11 or below) in the west to upper Frio (CC-2) in the southeast. As shown in the following discussion, this variation corresponds to the seaward progression of structural styles, particularly the occurrence of high-displacement growth faulting.

The velocity structure of the sediments in the Corpus Christi area, as determined from

FIGURE 22. Plot of interval velocity versus depth as determined from velocity surveys of four wells in the Corpus Christi study area.

sonic logs and velocity analyses of the seismic data, shows a similar division (fig. 22). From the surface to about 8,000 ft (2,400 m), velocity increases linearly with depth from 6,500 ft per second (1,950 m per second) to about 11,000 ft per second (3,300 m per second). Velocity decreases below 8,000 ft (2,400 m), reaching a minimum of 8,500 ft per second (2,550 m per second) at depths greater than 12,000 ft (3,600 m). This break in velocities has been interpreted to represent a response to undercompacted geopressed shale. However, no such break was observed in other Frio study areas. It is likely that the break primarily reflects the pronounced lithologic change from sand-rich strata in the upper section to shale-rich strata in the lower

section. The lithologic change reinforces whatever decrease in velocity is caused by geopressure.

Structural Development

On the basis of correlation of well logs and interpretation of seismic lines, a series of structure maps on selected horizons (figs. 23 through 26) and a set of sequential isopach maps (figs. 27 through 29) were prepared, and two seismic lines (figs. 30 and 31) were interpreted. A sequential isopach map of the X-Y interval (Y is deeper than X) represents an approximate paleostructural map of horizon Y at the time of deposition of horizon X (neglecting compaction) if horizon X was deposited near sea level,

FIGURE 23. Structure map contoured on CC-1 (top of Frio) showing large oil-bearing structures. Expansion index (thickness on downthrown side/thickness on upthrown side) shown for CC-1 to surface. Width of faults related to displacement (fault dip = 45° unless otherwise determined). W.P.E. = White Point East.

FIGURE 24. Structure map contoured on CC-4 (approximately *Nonion struma*). See figure 23 for explanation of symbols.

FIGURE 25. Structure map contoured on CC-9 (approximately *Textularia mississippiensis*). See figure 23 for explanation of symbols.

FIGURE 26. Structure map contoured on CC-11 (approximately *Anomalina bilateralis*). See figure 23 for explanation of symbols.

FIGURE 27. Isopach map of the CC-1 to CC-4 interval (upper Frio). See figure 23 for explanation of symbols.

FIGURE 28. Isopach map of the CC-4 to CC-9 interval (middle Frio). See figure 23 for explanation of symbols.

FIGURE 29. Isopach map of the CC-9 to CC-11 interval (lower Frio). See figure 23 for explanation of symbols.

FIGURE 30. Interpreted seismic section, near A-A', Nueces County.

FIGURE 31. Interpreted seismic section, near B-B', Corpus Christi Bay, Nueces County.

which is probably true of the Frio depositional systems considered here. Thus, the structures active at a certain time are more easily recognized on these maps. Isopach maps of the Corpus Christi area mimic the structural maps in most respects, except that they do not show post-Frio regional tilting, which indicates that structural activity became less intense with time and that no significant overprinting has occurred.

Three phases of structural development can be recognized on both the maps and the seismic sections. These phases form a sequence of waning shale mobility and fault intensity (measured by both displacement and frequency). The zone of maximum deformation progresses basinward, so that strata of successively younger age have a similar structural style toward the basin. This progression follows the progradation of the shelf margin by the barrier-bar/strandplain system.

The earliest phase having adequate data is characterized by large growth faults and a variety of shale tectonic structures. Expansion indices of large sedimentary sequences over the growth faults in this phase are more than 1.5 and often more than 2.0 (that is, twice as large on the downthrown side as on the upthrown side). Expansion indices as great as 5.0 can be documented for individual sand bodies; large expansions such as these place the lower boundary of the expanded isopach intervals below present drilling depths. Major displacement occurs on a few zones of faulting. The large growth faults consist of several strands that branch and rejoin, forming an anastomosing pattern. Smaller growth faults cross-link the major fault zones. Strata dip landward toward the faults but are highly modified by shale mobilization. Significant regional antithetic faults, formed on the landward side of a shale ridge, occur in the southern part of the area (fig. 29).

Three varieties of shale tectonic features are recognizable within this early phase. Discrete shale diapirs occur in the northern part of the area. These diapirs bring prodelta-slope shale of Vicksburg (early Oligocene) and Jackson (late Eocene) ages into contact

with lower and middle Frio strata (fig. 32). Growth faults are commonly found on the basinward sides of the diapirs. These diapirs are similar to those to the northeast described by Bishop (1977). Domes and domal anticlines with an inferred core of Vicksburg shale form high-relief, intensely faulted structures in the early structural phase. The northeast flank of the Mobil-David dome (fig. 20) in the southwestern part of the area has nearly 2,000 ft (600 m) of structural relief on the CC-11 horizon (fig. 33). Similar domes occur at Bohemian Colony (18S-21E) and Portland (17S-22E) (figs. 26 and 29). Strata on the crests of these features are broken by many normal faults having 100 to 300 ft (30 to 90 m) of displacement (figs. 29 and 33). Between and around the shale-cored domes, or "growth anticlines" described by Han (1982), are structural depressions, caused by shale withdrawal, that are analogous to salt-withdrawal basins associated with salt diapirs (no salt structures are found in the Corpus Christi study area). Information on these depressions is sketchy because they are sparsely drilled. The depression northeast of Mobil-David dome is fairly well documented (Morton and others, 1983; figs. 29 and 33). Similar shale-withdrawal basins are inferred to occur at 18S-21E, 18S-22E, and elsewhere in the area. The basins apparently are less affected by small faults than by growth anticlines. Because the basins subsided more rapidly than the growth anticlines during deposition, they localized a greater thickness of sand in each progradational unit.

The intermediate structural phase is characterized by less intense growth faulting and by systematic dip reversal of the strata. Growth faults of this phase have yield expansion indices of 1.2 to 1.8 (figs. 27 through 29). Thickest sediments were deposited on the immediate downthrown side of the major growth faults, whereas thin sediments were deposited on the farther basinward edge of each fault compartment. Continued normal faulting on listric surfaces causes rotation of beds into the fault plane, resulting in complete dip reversal, or landward dips in the overall gulfward-

FIGURE 32. Structure section across a shale diapir, San Patricio County; line of section shown in figure 20.

FIGURE 33. Structure section along structural strike from Mobil-David dome to Bohemian Colony dome; line of section shown in figure 20.

dipping Tertiary sequence (fig. 31). Shale tectonism is subdued, and the withdrawal basins are largely filled in; however, long-lived areas of lesser subsidence occur over some domes, perhaps because of the relatively greater loading of coarse clastics in the nearby basins.

The late structural phase consists of low-intensity growth faulting, which may have been reactivated intermittently to the present, and of associated rollover anticlines. The faults have expansion indices of less than 1.3 in most cases, commonly less than 1.1. These rollover anticlines are large, gently dipping, little-faulted structures and contain many of the large oil fields of the area (Aransas Pass, White Point East, Luby, and others; fig. 23). Rollover anticlines have origins similar to those of the deeper dip-reversed compartments. They formed closed anticlines because of the widely spaced faults at shallow depth and because the small displacements of the faults are insufficient to generate complete dip reversal. The major growth faults of the earlier phases generally continued to be active but only along certain strands, which are locally distinct from those on which most of the early movement occurred.

Geopressure in the area is mainly restricted to sands deposited in the first structural phase. The high fault density and the shale tectonic disturbances have isolated most sandstone bodies and maintained high pressures. Some of the deeper dip-reversed fault blocks, downdip of the larger faults of the second structural phase, are also geopressured. The sandstone-rich upper sequence was deposited during the second and third structural phases.

Three true-depth cross sections illustrate the nature and progradation of the structural phases (figs. 34A through C). The first phase is well developed primarily in the CC-11 horizon, which also shows shale tectonic effects over a broader extent than does any other horizon (figs. 29 and 34A). Most of the rest of the deeper part of the section illustrates the second structural phase (dip reversal), whereas shallower strata show basinward dip having gentle rollover anticlines.

Because of the large number of wells that were correlated, the variation of intensity of faulting with depth could be estimated by tabulating the intersections of faults with well bores; both displacement and depth encountered are listed (fig. 35). Many faults, when plotted, have less than 400 ft (120 m) of displacement at depths greater than about 9,000 ft (2,700 m). Faults of large displacement, however, continue into relatively shallow depths. To quantify this assessment, the number of faults in each 50-ft (15-m) interval was counted and plotted against depth on a histogram, which shows a maximum number of fault-well intersections (closed bars) at 9,000 to 10,000 ft (2,700 to 3,000 m). However, the decline in fault-well intersections below 10,000 ft is clearly a result of the smaller number of wells drilled to sufficient depth. Therefore, to estimate the geologic variable (number of faults), the fault histogram was corrected to include the projected number of fault-well intersections that would have occurred if all wells had been drilled to great depth. To perform this correction, the total depths of the 557 wells used were plotted against depth, and a cumulative frequency plot, $F(z)$, was made. The fault-well intersection frequency was then divided by $F(z)$ to yield the open-bar histogram, which was then smoothed by forward- and reverse-moving averages, producing an estimated curve of fault intersections per 100 ft. This curve quantifies the original qualitative estimate of increasing faults with depth and indicates a large jump in fault density between 8,500 and 10,000 ft (2,550 and 3,000 m); below that, fault density is essentially constant. The jump corresponds to the top of geopressure and indicates a close relation between the many small faults and the geopressure occurrence. The small faults may isolate the geopressured sandstones from the regional aquifer system, thereby allowing geopressure to be maintained.

One limitation of the foregoing technique should be mentioned. Deep oil and gas exploratory wells in the study area are drilled mainly on the domes and the structural highs, not in the withdrawal basins or in the areas immediately downdip of major growth

FIGURE 34. True-depth sections (A) A-A', southern Nueces County; (B) B-B', northeastern Nueces County; and (C) C-C', San Patricio County. Lines of sections shown in figure 20.

FIGURE 35. Plot of distribution of fault-well intersections with depth, Corpus Christi study area. TD = total depth of well; $F(z)$ = cumulative frequency of wells having total depth greater than the depth given, as a fraction of the total number of wells; GP = geopressure. Closed bars are raw values; open bars are adjusted for sample density (see text).

faults. These areas are probably less faulted than are the domes (fig. 33); hence, the estimate of fault density at depths greater than 10,000 ft (3,000 m) is probably too high. However, the aforementioned conclusions are not substantially altered.

The sequence of structural phases can be described in terms of the sequence of events of a prograding shelf margin outlined by Winker (1982). Phase one represents the initial progradation of the shelf margin onto the upper continental slope. Uncompacted shale, which may have formed an irregular surface because of sediment piling in the toes of earlier-formed growth-fault zones, was loaded by a rather thin shallow-water sequence. Shale became mobilized to produce large shale masses, diapirs, and active growth faults. Phase two represents a mature continental margin. The greater thickness of sediment overlying uncompacted shale reduced the buoyant instability of the shale (Bishop, 1977). Yet growth faults were still active, resulting in net translation of much of the continental shelf edge seaward on deeper lying detachment surfaces, which may lie in the Vicksburg or Jackson Formations (Ewing, 1982). Phase three began when the shelf margin had migrated seaward of the area. Many of the growth faults were stabilized. As basinward tilting continued, some of the growth faults were episodically reactivated, producing rollover anticlines of large extent. Such reactivation continues to the present, but displacements are slight.

Structural Constraints on the Occurrence of Geopressed Reservoirs

As noted previously, fault intensity at Corpus Christi generally increases with depth. Fault compartments in the geopressed zone typically are small and poorly defined. The largest unfaulted structures in the first structural phase appear to be the shale-withdrawal basins. These structures can be large and localize a thick accumulation of sand.

One of these shale-withdrawal basins was tested by the U.S. Department of Energy Well of Opportunity program. The Ross (Coastal

States) Pauline Kraft No. 1 well was drilled to the Anderson sand (CC-11) in the basin northeast of Mobil-David field. A relatively thick sandstone body having high fluid temperature was found, but the permeabilities were low. Because low permeability is a strong deterrent to geothermal development in South Texas (Loucks and others, 1981), finding zones of enhanced porosity and permeability in deep sandstone bodies is essential to developing geothermal reservoirs in this area.

Seismic sections indicate no great changes in structural style below the depth of currently available well control. More diapiric or incipiently diapiric slope shale is probable. The stratigraphy of the Tertiary Gulf Coast Basin suggests that no reservoirs of shallow-water origin occur below the Frio sands in this area. Sandstone reservoirs of deep-water origin may exist in the Vicksburg or older units and may be relatively large, but their lithology and internal properties are unknown.

Sarita Dip Section

A dip-oriented seismic section through part of the Frio growth-fault trend in Kleberg and Kenedy Counties (fig. 19) was interpreted. The western half of the seismic line crosses the middle of the Sarita prospect outlined by Weise and others (1981a) (fig. 36).

Previous work on the structure of Sarita was not reinterpreted, partly because of the difficulty of correlating electric logs there. Instead, a cross section of well logs incorporating the available paleontological data was drawn approximately parallel to the seismic line. This cross section was correlated together with the interpretation of the seismic section. The results are generally consistent with the previous correlations, although minor changes are indicated.

As shown in figure 19, the Sarita dip section crosses the north-central part of the Norias delta system of the Frio Formation in South Texas (Galloway and others, 1982). The Norias delta is marked throughout Frio time by a rapid seaward progradation, which

FIGURE 36. Structure map contoured on S5 horizon, Sarita prospect area, showing the line of section of figures 37 and 38 (from Weise and others, 1981a).

was terminated by a limited Anahuac transgression. This progradation extended the shelf margin some 40 to 60 mi (60 to 80 km) seaward in South Texas; the seaward limit of the delta system has not been delineated. Faulting, shale tectonics, and possibly salt tectonics accompanied the Norias progradation.

Stratigraphy

In studying the Sarita area, Weise and others (1981a) described the stratigraphy of the Frio Formation in terms of electric log correlation markers S1 through S8 (fig. 37), ranging from the top of the Frio to basal Frio strata. They divided the section into three parts: The section below S5 contains upward-coarsening sandstone and shale sequences several hundred feet thick that are interpreted to be progradational deltaic facies. Between S5 and S3 are shales and laterally discontinuous sandstones 10 to 90 ft (3 to 30 m) thick that are interpreted to be dominantly aggradational delta-plain facies. The upper part of the section contains persistent upward-coarsening sandstones. These may represent delta-front sandstones related to the transgressive episode from late Frio to Anahuac time.

Weise and others (1981a) did not attempt correlation of the S horizons with benthic foraminifer markers. Because benthic foraminifers were used in the present study (fig. 38), especially in the downdip area, approximate correlation of the S horizons with these markers is possible. The S1 marker represents *Heterostegina*; it is the top of the Frio updip of the Anahuac pinch-out but lies within the Anahuac in downdip sections. The S3 marker approximates *Cibicides hazzardi* (upper Frio), the S5 marker approximates *Nodosaria blaspiedi* (middle Frio), and the deep S7 marker correlates with the *Anomalina bilateralis* horizon (lower Frio). The top of the Vicksburg, taken here as the first occurrence of *Textularia warreni*, was not included in the earlier marker scheme but lies below S8. The datum formed by the last appearance of each marker species in the Corpus Christi study

area rises basinward through the section; hence, species correlations to log markers are only approximate.

Correlation of well logs in and downdip of the Sarita area is unreliable at best, owing to the dominantly aggradational delta-plain setting of much of the section and to rapid, unpredictable expansions caused by growth faults. To confirm the well log correlations, seismic reflection facies were analyzed by noting on an overlay both the faults determined from seismic data and significant reflectors. Depths of paleontologic horizons from nearby wells were converted to travel time, plotted on the overlay, and checked with the reflector picks. The character of reflector packages was then noted on the overlay and displayed in figure 39. Five seismic reflector facies were distinguished. High-frequency, low-continuity reflectors of varying amplitude dominated the higher parts of the section and were locally present at depth. Reflectors of high amplitude and frequency and of good continuity were locally within the first facies and in a band below the first facies. Chaotic reflectors, including noise zones, predominated at greater depth. Local transparent zones occurred within the upper facies. Strong, low-frequency, continuous reflectors appear at approximately 6 seconds on the section.

These reflector facies may be interpreted in terms of overall depositional environments. The upper discontinuous facies represents the aggradational delta-plain and fluvial systems in the Frio Formation and overlying strata; such environments usually have discontinuous sandstones in a shale matrix. The band of continuous reflectors marks the deltaic progradational environment in which sandstones are more continuous and correlatable. The chaotic facies largely represents prodelta/slope shale sequences and includes a shale mass behind the major growth fault. The deep low-frequency facies may represent Cretaceous carbonates or even older rocks deeper than 30,000 ft (9,000 m). Facies geometry shows the strong progradation of the shelf-margin shales over slope shales and of the delta-plain sediments over the delta-front sedi-

FIGURE 37. Structural dip section H-H', Sarita prospect area (from Weise and others, 1981a). Compare with figures 21 through 23.

ments. Anahuac transgression is visible at the east end of the section. Results of the reflector facies analysis were used to check the reflector correlations across major growth faults and the correlations on the well log section (fig. 38).

Geopressure occurs at a depth of 9,500 ft (2,850 m) at the west end of the line to about 9,000 ft (2,700 m) at its midpoint and eastern end (Weise and others, 1981a). This falls generally at the *Nodosaria blaspiedi* horizon (S5) in the Sarita area but is higher in the downdip part of the section. The top of geopressure follows the base of the delta-plain-dominated facies and the top of the shale-rich delta-front and prodelta section. The pod of sand-rich delta-plain facies indicated in figure 39 is also geopressed and might be a potential geothermal prospect.

Structural Development

The interpreted seismic section is shown in figure 40; a true-depth section is constructed from it in figure 41. Both sections are dominated by a large low-angle listric growth fault backed by a shale ridge of diapiric or semidiapiric Vicksburg and pre-Vicksburg shales. Antithetic faults are moderately abundant, and substantial rollover of strata into the fault is indicated. Other growth-fault systems having a generally steeper dip angle are interpreted to lie downdip of the major fault; at least one system may converge with the major fault at depth.

Shallow strata are gently folded into rollover anticlines downdip of growth faults. Deeper strata dip landward into the major growth fault and are broken by antithetic faults. This landward dip is also shown on the structure map by Weise and others (1981a) of S5 (approximately *Nodosaria blaspiedi*) (fig. 36). The downdip growth faults seem to have caused comparatively little rollover, although some dip reversal appears on one fault. The area on the right-hand side of the seismic section may be related to the toe of material moved seaward on the low-angle detachment surface of the updip major growth fault.

There is little evidence of intense faulting below the top of geopressure, unlike the Corpus Christi area. An absence of extensive faulting can be attributed partly to the poor well control downdip, which allows the interpreter to gloss over minor faults. The lack of abundant faulting in the deeper section may reflect the relative lack of shale diapirism immediately downdip of the western shale ridge. Shale buoyancy formed a shale ridge behind the major fault and may have been active at the east end of the section in an area of reverse dips and possible local unconformities. The area between these localities is affected by growth faults but shows little other shale tectonic activity.

Much basinward sliding occurred on the low-angle growth fault. Palinspastic reconstruction of the left-hand part of the line indicates a post-Vicksburg extension of about 25,000 ft (7,500 m), or 50 percent (fig. 42). Most of this extension took place before middle Frio (*Nonion struma*) time; later extension was only 7,000 ft (2,100 m). The shale ridge developed early (pre-*Anomalina bilateralis*), as shown by thinning of basal Frio and Vicksburg reflector packages over the ridge. Post-*Anomalina bilateralis* strata show little thinning over the ridge but large expansion over the growth fault. An early-formed shale ridge backing a later growth fault was noted elsewhere in South Texas (Bruce, 1972).

Structural Constraints on the Occurrence of Geopressed Reservoirs

Geopressed reservoirs of possibly large extent occur in the downdropped strata basinward of the major growth fault at Sarita. Many of the sand-bearing units here have already been drilled for gas (fig. 38). However, no sand bodies are known to occur in the Vicksburg in this downdip position (Loucks, 1979), so future prospects are discouraging. Poor reservoir quality is also a major problem in the Sarita area, as discussed previously.

FIGURE 38. Structural dip section constructed near the seismic line. Line of section shown in figure 25. Horizons

shown are based on log and seismic interpretation but approximate the benthic foraminiferal horizon shown.

FIGURE 39. Seismic reflector facies interpretation of seismic line. Top of Frio (TF) is *Cibicides hazzardi* on this section; top of Vicksburg (TV) is *Textularia warreni*.

FIGURE 40. Interpreted seismic section, Sarita dip line.

FIGURE 41. True-depth structure section constructed from seismic line and well data.

Port Arthur Study Area

The Port Arthur study area is located in the Frio (or Frio-Vicksburg) growth-fault trend in far southeast Texas, including much of Jefferson and Orange Counties (fig. 43) and the Port Arthur and Port Acres gas-condensate fields, which were studied for possible dispersed gas production (Gregory and others, 1984). More than 220 electric logs from deep wells have been correlated. Six seismic lines, acquired and reprocessed for the dispersed gas study, were interpreted along with the well data.

The study area lies in the western part of the Hackberry Embayment (Paine, 1968), within which the Hackberry deep-water member of the Frio Formation was deposited (fig. 44). The Hackberry forms a seaward-thickening wedge in southeast Texas and southwest Louisiana that lies within the Frio marginal-marine succession of the Buna barrier-bar/strandplain system and possibly the marginal parts of the Houston delta system described by Galloway and others (1982) (fig. 19). The wedge pinches out to the north along a line that Bornhauser (1960) termed the Hartburg flexure. The lower Hackberry is a sand-rich unit that fills channels eroded as much as 800 ft (250 m) into the pre-Hackberry sediments (fig. 45). Studies by Paine (1968), Berg and Powers (1980), and Ewing and Reed (1984) indicate that these sands formed in a submarine canyon-fan environment. These lower Hackberry sands are currently the most productive geopressed exploration target in the region.

Three salt domes are wholly included in the area: Spindletop, Port Neches, and Orange. In addition, two salt domes, Fannett and Big Hill, lie along its boundaries, and a probable salt dome, McFaddin Ranch, is in the southern part of the area.

Stratigraphy

The Frio Formation at Port Arthur ranges from about 2,000 to more than 6,000 ft (600 to more than 1,800 m) thick, increasing basinward. Updip, the Frio consists of stacked barrier-bar and strandplain sand-

stones of the Buna barrier system. Downdip, the sandstones are less abundant, and the deep-water sand-shale wedge of the Hackberry appears.

The Frio can be divided into three units (fig. 46). The lower unit (between *Textularia warreni* and *Nodosaria blanpiedi*) is thin and sandstone-poor; it is difficult to distinguish from the underlying Vicksburg. The middle unit (from *Nodosaria blanpiedi* to about *Marginulina texana*) contains abundant sandstone updip but only a few discontinuous sandstones of unknown origin down-dip; the downdip sandstones are extensively eroded at the sub-Hackberry unconformity, and their original thicknesses and geometries are obscure. The Hackberry wedge lies between *Nonion struma* and *Marginulina texana* in the upper part of the middle Frio. The upper unit consists of nearly continuous sandstone updip and alternating sandstone and shale downdip. These sandstones contain upward-coarsening cycles and are continuous along strike; however, they shale out fairly rapidly downdip and are inferred to be barrier-bar sandstones, strandplain sandstones, or both. They are overlain by transgressive shallow-marine shales of the Anahuac Formation. Within the Anahuac Formation is a locally developed limestone member known informally as the *Heterostegina* limestone. Undifferentiated sandstone and shale of Miocene age overlie the Anahuac.

The Vicksburg Formation, which here underlies the Frio, consists largely of shale. Resistivity of the Vicksburg shale is typically higher than that of the lower Frio, but the two strata are otherwise similar. Within the Vicksburg are discontinuous sandstone bodies having blocky spontaneous potential patterns similar to those of the Hackberry sandstones; this suggests that some of the Vicksburg sediments represent deeper water (slope?) deposits.

Within the downdip parts of the study area, no units below the pre-Hackberry unconformity can be correlated in enough well logs to determine their structure reliably. Furthermore, the seismic data are not of good enough quality to determine the deep structure. Well log correlation markers were

FIGURE 43. Location map of Port Arthur area showing well control, general locations of seismic lines, and locations of salt domes.

FIGURE 44. Map showing regional distribution of sandstone-bearing lower Hackberry channels in Hackberry Embayment west of Acadia Parish, Louisiana. Louisiana data from Paine (1968); Texas data from Bornhauser (1960) and this study. The type locality of the Hackberry at Hackberry salt dome is also shown.

FIGURE 45. Interpreted dip- and strike-oriented seismic lines, Sabine Lake. Location of lines shown in figure 43.

FIGURE 46. Stratigraphic diagram of Frio and related strata, Jefferson County study area, showing diagnostic foraminifers, sand-body distribution (shaded), and electric log marker horizons used in this study (A1 through A5).

therefore set up from A1 through A5, ranging from the top of the Anahuac to the pre-Hackberry unconformity (fig. 45). Progradation of the upper Frio and lower Miocene sandstones is indicated because their respective markers pass updip from shale to sandstone sequences. Markers A1 through A3 lie in shallow-water deposits, whereas markers A4 and A5 lie in deep-water strata of the Hackberry unit.

In most of the study area, the top of geopressure is near A3, the base of the upper Frio sandstones (fig. 47); the Hackberry and deeper sandstones southeast of Spindletop salt dome are geopressed. In the north-

western part of the area, the top of geopressure lies below the base of the Frio; this was noted near the Lear Koelemay No. 1 (Morton and others, 1982). In downdip wells where the upper Frio is sand-free, the top of geopressure rises into the upper Frio and probably to the base of the Miocene. In the Port Arthur-Sabine Lake area, the top of geopressure coincides with a sharp drop in seismic velocity (fig. 48). However, the effects of geopressure at A3 are coincident with the lithologic transition from a sandy to a shale-dominated sequence; hence, the effects of geopressure on velocity cannot be adequately assessed. The lower Hackberry sandstone

FIGURE 47. Structure section C-C' near Port Arthur field and Spindletop dome.

FIGURE 48. Plot of interval velocity versus depth for two velocity surveys and velocity analyses from seismic data. Stratigraphic horizons shown for the velocity surveys.

shows higher velocities than does the Hackberry shale, although not as high as extrapolation of values from shallower sandstones would indicate.

Structural Development

Well log data were combined with the available seismic sections to construct structure maps and sequential isopach maps (to approximate paleostructure or paleogeography) of the Port Arthur area. Analysis of these maps suggests four phases of structural activity.

Well penetrations below the Hackberry sequence are sparse, and a reliable top of the Vicksburg is difficult to pick from the logs available. However, with paleontological information and limited well log correlation, an isopach map from A3 to the top of the Vicksburg can be sketched (fig. 49). (The A4 and A5 markers could not be used for this isopach map because they are known to have been much below sea level; in addition, A5 is an irregular, unconformable surface.) This map identifies elements of the first phase of structural development. Two broad uplifts, inferred to be salt-cored, underlie the northern half of the area: one under the younger Orange and Port Neches salt domes and the other under Spindletop salt dome and farther west (fig. 49). A depression north of the uplifts and a sag between the uplifts and to the south suggest salt movement into the uplifts. The large, irregular changes in thickness in the southwestern part of the area suggest a growth fault having some combination of dip-reversal and salt-generated activity. One shale diapir yielding Jackson-age (Eocene) fossils has been drilled below the Hackberry. Development of the area before deposition of the upper Frio seems to be the result of shale tectonic growth faulting and broad salt uplifts.

Where the lower Frio and Vicksburg shelf margins lay is unclear. Sandstones found within the Vicksburg lie in the southwest and central parts of the Port Arthur area and appear to be similar to Hackberry sands. These sandstones were probably deposited in deep water on the continental slope. The depositional environment of the lower Frio is

debatable, but faunal evidence in Chambers County to the west suggests shallow-water deposition (Gernant and Kesling, 1966). Shelf deposition of the lower Frio is generally assumed to be true elsewhere in the Hackberry Embayment. If deposition was indeed in shallower water, then the shelf margin prograded across the study area during late Vicksburg and Frio time, but virtually no sand marks this progradation. This progradation may be an example of progradation of a mud-dominated shelf margin. Other examples on the Texas Gulf Coast include the Yegua-Jackson-Vicksburg progradation immediately northwest of the Port Arthur area in Jefferson and Hardin Counties (Morton and others, 1983) and the Claiborne progradation in parts of Central and South Texas. In any event, some of the structural activity shown in figure 49 occurred while the area was at or seaward of the shelf margin.

The second phase of structural development was the formation of the Hackberry Embayment and its filling by deep-water shales and channel sands. A pre-Hackberry unconformity (A5) was developed over the entire area downdip of the Hartburg flexure, which is marked by a zone of growth faulting. This unconformity is interpreted by most workers to reflect subsea erosion of varying intensities related to submarine fan deposition downdip and to the immediately overlying channel-fill sands. If the lower Frio was of shallow-water origin, as discussed, then a large-scale, rapid foundering of the shelf margin must account for the formation of the Hackberry Embayment. If, however, the lower Frio was deposited in deep water, the Hackberry may be related to either deltaic progradation to the west or eustatic sea-level fluctuations (which were proposed by Coleman and Prior [1982] to explain Pleistocene channels in offshore Louisiana).

An isopach of the A3-A4 interval (fig. 50) further reveals the structural elements active during Hackberry time. The large uplift in Orange County had split into two broad uplifts centered on Orange and Port Neches salt domes. The first-phase uplift in Jefferson County appears in the second phase as a

FIGURE 49. Isopach map of A3-Vicksburg interval, Port Arthur area, showing broad uplifts and depressions during lower Frio deposition.

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FIGURE 50. Isopach map of A3-A4 interval, Port Arthur area, showing salt uplifts and major growth faults influencing Hackberry deposition.

north-south elongate high extending from Lovells Lake south to La Belle field (field locations on fig. 51). This north-south high has a sharp eastern margin, which may be faulted in some areas; however, no fault has been identified from the structural data on A4 (fig. 51). Sand-filled Hackberry channels cut across all the highs. Activity on the many small growth faults indicated in figure 51 probably occurred throughout Frio time; however, displacements are small (fig. 47).

After the area was infilled nearly to sea level by Hackberry shale, the barrier-bar system of the upper Frio prograded to the shelf margin. The third-phase structures then active are shown on an isopach map of the A1-A3 interval (fig. 52); A1 is used rather than A2 to increase the accuracy of the measurement. During this time, the Orange and Port Neches salt uplifts were narrower than before. The north-south high area extended northeastward past the present-day Spindletop salt dome; the southern part of the high area was cut by growth faults. A rapidly thickening section in the southern and southeastern margins of the area, in part occurring along large growth faults through Big Hill and McFaddin Ranch salt domes, probably marks the upper Frio and Anahuac shelf margin.

Structural elements active during Anahuac time also are shown on an isolith map of the *Heterostegina* limestone (fig. 53). This limestone formed reefs around several salt domes and salt uplifts in southeast Texas; it probably accumulated wherever uplifts raised the seafloor above the muddy bottom. In the Port Arthur area, the limestone forms an east-west band across the area lying between the updip margin of the Anahuac and the downdip limit of environments favorable for carbonate deposition. Within this band, three pinnacle-reef accumulations (more than 100 ft [30 m] thick) occur; these are at Hildebrandt Bayou, Port Neches, and Orange fields. A similar thick accumulation occurs around Fannett salt dome immediately west of the study area. These reefs correspond to the Orange and Port Neches salt uplifts and to the Lovells Lake-La Belle salt-cored ridge. No thick limestone accumu-

lation is known to occur at Spindletop salt dome; the maximum true limestone thicknesses there are only 80 to 85 ft (24 to 26 m). The isolith contour suggests an atoll-shaped limestone, which is centered immediately north of Hildebrandt Bayou field.

Post-Anahuac activity, the fourth phase of structural development, is best shown on the A2 structure map (fig. 54). Uplift of the Orange and Port Neches salt domes continued, as did uplift of Big Hill, McFaddin Ranch, and Fannett salt domes. Spindletop salt dome grew from the older salt-cored high, which retained only a subdued expression. Continued activity on regional growth faults in the area created the rollover anticlines that localize many important oil fields (Amelia, West Beaumont, Lovells Lake, and La Belle fields). The Miocene shelf margin prograded seaward beyond the southern boundary of the study area. A south-southeast regional dip developed on all horizons.

Several significant features can be summarized. Salt and shale tectonism together were active for a long time. Growth faulting is generally of low displacement; however, abundant and long-lived growth faults at the shelf margin may have moved substantially in some periods. Salt uplifts of large lateral extent existed from Vicksburg to Miocene time, becoming gradually more restricted and more diapiric. Spindletop, a prolific oil-producing dome, formed late in the tectonic sequence, rising from an older salt-cored ridge. Port Neches and Orange salt domes, which show steady development through time, are important oil-producing domes but not as significant as Spindletop. The oil at Spindletop may have resulted from Miocene draining of parts of the earlier-formed salt uplift. The Hackberry deep-water erosional and depositional episode clearly is superimposed on the coexisting salt and shale tectonism, although its origin remains elusive.

Structural Constraints on the Occurrence of Geopressured Reservoirs

Currently available data are inadequate for a discussion of the structures that exist at

FIGURE 51. Structure map contoured on A4 horizon, Port Arthur area.

FIGURE 52. Isopach map of A1-A3 interval, Port Arthur area, showing salt uplifts and significant growth faults influencing upper Frio and Anahuac deposition. More faults were active than are shown.

FIGURE 53. Isolith map of *Heterostegina* limestone (middle Anahuac). Within a broad belt of thin limestone, pinnacle reefs formed at Hildebrandt Bayou, Orange (Bridge City), and Port Neches uplifts. Reefy limestones mark topographic highs during Anahuac transgression.

depth within the Vicksburg and deeper strata. The shallower structures indicate, however, that strike-elongate, rather narrow fault compartments are to be expected, variably modified by salt withdrawal (fig. 51). These compartments are similar in shape to those of the Wilcox fault trend in the Cuero area (Winker and others, 1983) and are unlikely to yield large reservoir volumes where they crosscut dip-oriented sandstone bodies such as the Hackberry sands. Some of the Hackberry sandstones, however, have more of a blanket geometry (for example, the C sand at Port Arthur; Gregory and others,

1984) and might have a more substantial aquifer volume.

The study area lies in a sandstone-poor region of the Oligocene continental margin. Sand appears to have been supplied by longshore transport from either the Houston delta to the west or unknown sources in Louisiana. Progradation of the shelf margin seems to have been accomplished by muddy sediments rather than by sandstones; little evidence of expansion of the Frio sandstones across growth faults can be found. A similar mud-dominated margin may have existed in the Yegua Formation in northwestern

FIGURE 54. Structure map contoured on A2 horizon, Port Arthur area. Structures producing oil from strata near A2 are named.

Jefferson County near the Lear Koelemay No. 1 well of opportunity (Morton and others, 1983). This margin is characterized by generally subdued structures and closely spaced, low-displacement, long-lived growth faults. Geopressed geothermal prospects are poor in these areas.

Discussion

The Bureau of Economic Geology has studied five areas along the Frio growth-fault trend of the Texas Gulf Coast to determine local structural history and geothermal potential. From south to north, these areas are Sarita, Corpus Christi, Blessing, Pleasant Bayou, and Port Arthur. (Studies of Blessing and Pleasant Bayou were reported by Winker and others, 1983.) In addition, the far South Texas Frio trend in the McAllen-Pharr area was studied by Han (1983). The even spacing of these study areas, which represent most of the major downdip depositional systems of the Frio Formation (fig. 18), allows us to make significant generalizations about the entire Frio growth-fault trend.

Comparison of Structural Styles of the Five Frio Study Areas

One distinction between the part of the growth-fault trend east and northeast of central Matagorda County and the part to the southwest is evident on regional fault maps (fig. 1). The eastern part is dominated by conspicuous salt tectonic features: salt domes, salt-cored anticlines, and salt-withdrawal basins. In contrast, the region southwest of Matagorda County is marked by long belts of growth faults, shale diapirs, and shale ridges, which are manifestations of shale tectonics. In the past, these regions were considered separately, and separate processes were attributed to each. However, studies reported by Winker and others (1983) at Pleasant Bayou indicate that at least part of what has been called the salt tectonic region had a shale tectonic phase during shelf-margin progradation. This shale phase was then distorted by salt diapirism; the phase can be recognized only by careful seismic

and well log interpretation, coupled with sequential isopach mapping. The first distinction to be made within the Frio growth-fault trend is between those areas in which shale structures and growth faulting have been distorted by salt tectonism (Pleasant Bayou and Port Arthur) and those in which they have not (Blessing, Corpus Christi, and Sarita).

A second variation is the extent and timing of progradation of the shelf margin. In the southern areas (Sarita and Corpus Christi), progradation began with the early Frio and continued through most of Frio time. The shelf margin prograded steadily basinward, and the structural styles migrated with the margin. In the Blessing study area, no significant progradation could be seen. At Blessing and at Pleasant Bayou, the Frio shelf margin prograded basinward only during early Frio time; subsequently, the shoreline fluctuated with the deposition of individual delta lobes but slowly retreated landward (Winker and others, 1983). In the Port Arthur area, the strike-fed Frio sand system prograded basinward during middle to late Frio time over a previously established mud-dominated margin and muddy slope, which had foundered and received the deep-water sediments of the Hackberry Member.

A third variation among study areas concerns the depositional systems in which they developed during Frio time. Sarita occurs within the Norias delta system, Corpus Christi and Blessing within the Greta/Carancahua barrier-bar/strandplain system, Pleasant Bayou within the Houston delta system, and Port Arthur within the Buna strandplain and the Hackberry submarine canyon-fan system.

Because of these variations, each study area has a unique structural history. Shale tectonism at Sarita formed one or more shale ridges, one of which appears to have localized a major low-angle growth fault, trapping a wedge of deltaic sediments at considerable depth. At Corpus Christi, shale tectonism created large growth faults, shale-cored domal anticlines, and shale-withdrawal basins in deep structural levels; all these structures become progressively younger

basinward. Higher levels display the more typical patterns of dip reversal and rollover anticline. These higher levels also occur at Blessing; shallow-level rollover anticlines pass downward into reversed dip strata and into major growth faults. Shale diapirs in the lower Frio are known to occur nearby (Bishop, 1977). Lack of progradation in the Blessing area appears to have resulted in a narrow growth-fault zone; most Frio-age growth-fault activity was restricted to a few large faults. At Pleasant Bayou, a major early-formed fault displacement caused dip reversal and deposition of thick sandstone units against itself (Winker and others, 1983) similar to that at Blessing. Salt tectonism prevailed in the upper Frio and Anahuac, causing diapiric intrusion of Danbury salt dome and formation of a major salt-withdrawal basin. An early stage of salt movement may have formed the Chocolate Bayou domal anticline as a turtle structure; this movement possibly took place while the area was basinward of the shelf margin (Winker and others, 1983). In the Port Arthur area, low-displacement, long-lived faults defining narrow, strike-elongate fault compartments formed along the mud-dominated margin. Salt tectonism was active during growth faulting and may either have localized or have been localized by some growth faults. No progradation of structural styles can be inferred, except that post-Yegua (Vicksburg?) sand-poor progradation built up the shelf margin. The foundering of the area during the middle Frio is apparently due to sediment bypass and normal subsidence (Ewing and Reed, 1984), accompanied by secondary canyon cutting.

These contrasts among study areas can be considered in the context of the history of the Texas Gulf Coast. Frio sedimentation occurred over a preexisting clastic shelf margin established in Vicksburg time. To the south, a deltaic system in the Vicksburg had built a large platform basinward (Loucks, 1979); to the north, a mud-dominated margin persisted until the shelf margin was slightly advanced by the East Texas Vicksburg delta (Gregory, 1966). A mud-dominated margin also may have been produced in overlying

slope sediments of far southeast Texas. Landward of the entire Vicksburg progradational package is the Vicksburg fault zone, a major structural feature characterized by low-angle listric growth faulting, great expansion of the Vicksburg sediments, and a modified décollement surface in lower Vicksburg or Jackson (Eocene) geopressured slope shales.

In early Frio time, two deltaic systems prograded seaward over the Vicksburg shelf margin. The Norias delta in South Texas built out over one or more linear shale ridges and formed at least one low-angle growth fault. Initial loading of strandplain sediments marginal to the Norias delta caused intense irregular shale tectonic activity in the Corpus Christi area; the activity may have extended farther north and east. The Houston delta in East Texas prograded nearly to its maximum extent in early Frio time, loading the Vicksburg continental slope and causing large-scale growth faulting and possibly other shale tectonism. The margin was passive in far southeast Texas and had thin layers of mudstones. Most Frio growth faults are moderate-angle listric normal faults; some may merge downward with the Vicksburg décollement surface.

In middle Frio time, the Norias delta system and its flanking strandplain system continued to prograde basinward. The early shale-generated structures were subdued by burial with delta-plain and fluvial sediments, and new bands of intense growth faulting were established farther basinward. The barrier-bar system in Central Texas was virtually static, so that the early-formed growth faults were continually reactivated. A similar situation existed in the Houston delta system, although limited progradation may have occurred in some places. Loading by the lower Frio shelf margin of salt masses that previously had lain on the continental slope initiated salt remobilization and diapirism. In southeast Texas, salt continued to move into broad uplifts as a strandplain system began to prograde across the area. A large segment of the old shelf margin foundered; it was eroded by submarine canyons and was filled with deep-water sand and mud.

In late Frio time, the Norias delta and its adjoining strandplain system reached their maximum basinward extent and began to retreat landward. The Houston delta system and the strandplain to the south continued a slow retreat, and the shelf margin gradually stabilized. Salt tectonism became steadily more intense, and the present-day pattern of salt domes and salt-withdrawal basins began taking shape. The strandplain system in southeast Texas, however, continued to prograde over the older deep-water strata until Anahuac transgression ended Frio deposition.

During deposition of the Anahuac, the Frio progradational package was covered by shallow-marine strata. In South Texas, this progradation was limited and late; not all the Frio growth-fault trend was covered. In East Texas, the transgression began earlier, continuing the upper Frio shoreline advance, and it extended farther landward. Limestones accumulated over bathymetric highs on the transgressed shelf, outlining salt diapirs and anticlines. Miocene depositional systems then prograded over the submerged shelf and began to create a new prograding shelf margin, which now lies offshore.

Structural Constraints on the Occurrence of Geopressured Reservoirs

Previous workers studying the Blessing and Pleasant Bayou prospects did not assess the size of fault compartments (blocks of strata enclosed laterally by faults) and possible geopressured reservoirs at depth because they were concerned with known drilled-out geopressured reservoirs. In this report, however, fault compartment sizes and all possible geopressured reservoirs are relevant; therefore, these areas will be discussed briefly. The Blessing prospect lies within a fault compartment showing dip reversal of strata between widely spaced growth faults. Because of the strike-oriented geometry of the depositional system, reservoir volumes within this compartment were large enough to produce a favorable geothermal prospect. Similar reservoirs could occur at many points along the

Greta/Carancahua barrier-bar/strandplain system where similar conditions exist. The presence of thick sandstone is the major limitation. At the Pleasant Bayou test well site, the prospect was formed by a combination of an early-formed, immense dip-reversed fault compartment between growth faults and a late-formed salt-withdrawal basin. The favorable combination of these two types of structures may be unique to the Pleasant Bayou area. At neither Blessing nor Pleasant Bayou can a significant increase in faulting with depth be detected; however, the study areas were rather small, and sample size may not have been sufficient to allow definitive conclusions.

Production of geopressured geothermal energy requires a producing aquifer of sufficient volume to maintain the system; therefore, the aquifer should be as large as possible. The areal extent, in turn, depends on the shape and orientation of the depositional sand body, the size, shape, and orientation of the fault compartment, and the sealing or nonsealing character of the faults. By applying this general outline to the aforementioned study areas, we can compile a short list of optimum structural configurations for large reservoirs.

Salt-withdrawal basins have large areas of nominally continuous strata, which have the advantage of being, by definition, off-structure. Geothermal production, therefore, is unlikely to compete with conventional hydrocarbon production. However, as seen at Pleasant Bayou, a salt-withdrawal basin of simple contour may mask the deep structure formed earlier; hence, prospects in these basins must be approached with care. Furthermore, salt-withdrawal basins are rarely drilled by exploration companies, so control is sparse. Early-formed withdrawal basins may invert to turtle structures because of continued salt mobilization. These large unfaulted domes would be ideal for geothermal production except that they are also ideal for conventional hydrocarbon production.

In areas of intense shale tectonism such as Corpus Christi, shale-withdrawal basins may

have been created that are similar to but smaller than the salt-withdrawal basins of the upper coast. As do the salt basins, these tend to be equidimensional and to contain a fairly large area of unfaulted strata. Medium-sized geothermal prospects, off-structure to most hydrocarbon activity, could be found here, given appropriate reservoir quality.

Fault blocks between widely spaced growth faults offer the most opportunities for finding large geothermal prospects. Both Blessing and Pleasant Bayou prospects are of this fault type. The Frio fault systems tend to be widely spaced except in far southeast Texas; hence, more area is available between them than is available between systems in the Wilcox growth-fault trend. Fault compartments of this shape are most efficiently

occupied by coalesced strike-oriented sandstone bodies, such as those of the Greta-Carancahua barrier-bar/strandplain system; however, deltaic systems having an unusually broad fault compartment or coalescing sandstone bodies, such as at Pleasant Bayou (Tyler and Han, 1982; Winker and others, 1983), also may form good prospects. The least faulted compartments may occur between the shale diapiric ridges that back some growth faults; the areas abutting or lying atop the ridges may tend to be highly faulted, as at Sarita and Corpus Christi. One disadvantage of this type of compartment is that the structurally high part of the reservoir is prospective for conventional hydrocarbons; however, as at Blessing, suitable geothermal reservoirs may also be found.

REGIONAL FAULT COMPARTMENT GEOMETRIES OF THE WILCOX AND FRIO TRENDS

Introduction

To extend the detailed data from the study areas to the entire region, faults and fault compartments in both Wilcox and Frio growth-fault trends were studied statistically. Emphasis was placed on fault compartments for several reasons:

- A growth fault generally merges into other faults; hence its ends are not easily defined. A fault compartment, given adequate subsurface mapping, is shown to be a distinct entity.
- Most geopressured reservoirs are bounded by faults on at least one side; many are entirely fault bounded. Hence, consideration of the fault compartment size and geometry is necessary to assess reservoir area and volume. This analysis is especially useful in the highly faulted areas common in the deep geopressured trends.

- Information on fault compartment sizes and fault spacings can be used with original sand-body geometry information (when compiled) to predict the distribution of reservoir sizes within a major progradational package.

Methods

To achieve regional coverage, commercial structure maps of the Gulf Coast structure were used. In general, the deepest horizon available was selected in each area; however, some areas were examined on two horizons. The fault pattern studied was commonly near the top of geopressure. The areas of the Gulf Coast examined, with numbers of compartments found per Tobin grid (7.5-minute quadrangle), are shown in figure 55. In all, 568 closed compartments were identified and measured.

FIGURE 55. Map of study area, Texas Gulf Coast, with numbers of closed compartments found per Tobin grid (7.5-minute quadrangle).

The accuracy of this sort of regional structure mapping is of some concern. In general, the well density is sufficient for determining the structural configuration at the horizons mapped (fig. 56). The only significant area of sparse control is the South Texas Frio, which was not included in this study. Maps of the Houston Diapir Province are considered to be somewhat less reliable than those of the southwest, because salt diapirism modified or masked earlier-formed growth-fault structures (Ewing, 1983).

Each closed fault compartment was characterized (fig. 57) by location (using the Tobin-GEOMAP location system), mapping horizon, average depth, area of the compartment (A , measured by planimeter, in mi^2), azimuth (α) of the long axis of the compartment, length of the long axis (a), and distances to the sides of the compartment from the midpoint of the long axis C_1 and C_2 (in feet, taken as negative going toward the Gulf of Mexico). The long axis was chosen as the line joining the corners of the compartment that are farthest apart.

These raw data can be transformed into a set of shape factors, which describe the form of the compartment. This transformation helps in visualizing the "typical" fault block and in comparing blocks of different sizes from different trends. The shape factors used are location, depth, datum, area (also plotted as log area), azimuth, oblateness, elongation, and curvature.

Oblateness (Ω) is measured by comparing the area of the compartment (A) to the area of an equivalent rectangle (A_r , formed by the long axis) and the difference between the midpoint measurements (or the short axis). The factor $\Omega = A/A_r$ equals 0.785 for a hypothetical elliptical compartment and 0.5 for a diamond-shaped (rhombic) compartment.

Elongation (E) is the ratio of the long axis (a) to the short axis (ΔC). Where this is in unity, the long and short axes are equal.

Curvature (κ) of the compartment is determined by drawing a circle, using the long axis (a) as chord and the midpoint of the short axis (ΔC) as a point on the circle (at a

distance, C , from the midpoint of the long axis). This value is the reciprocal of the radius of curvature (R_c). The curvature is negative for compartments that are convex basinward. A more enlightening graphical representation portrays the logarithm of the absolute value of curvature because curvature values vary by several orders of magnitude.

These transformed data were then separated into 11 sectors, 5 each along the major Wilcox and Frio-Vicksburg structural trends and 1 in the Mesozoic trends. The calculated values were plotted on histograms for each sector, as well as aggregated for the Wilcox and Frio trends. Histograms for selected parameters in the two trends are shown in figures 58 and 59, and a summary of all values by sectors in table 1.

Discussion

Distributions

Subtle but distinct differences between the Wilcox and Frio fault compartment geometries (table 1) can be detected; comparatively little difference exists between sectors within a trend. Wilcox fault compartments tend to be somewhat more uniform in area, are more elongate (except in sector 7, which lies in the Houston Diapir Province), are less oblate, and show a lower absolute curvature. Frio fault compartments show a greater range in compartment areas (some being very large; this may be an effect of sample size), are less elongate, are slightly more oblate, and commonly show higher curvatures. These variations are consistent with those observed in the fairway studies by Bebout and others (1978, 1982) and the area studies by both Winker and others (1983) and those presented in foregoing sections.

The distribution of compartments within both trends show a pronounced skewness that includes large values. Plotting values of log area gives an approximately normal distribution; however, this is probably an artifact of the measuring process. Small fault compartments are hard to locate and map because of limited well control; regional

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FIGURE 56. Map of well density, Texas Gulf Coast, in wells per 620 mi² (1,000 km²), from the Tectonic Map of Texas (Ewing, in preparation). The low values in 28-29 N. 97-98 W. do not reflect poor GEOMAP control but correspond to an area of deeper mapping for the Tectonic Map of Texas. L = over 150 wells per 620 mi² (1,000 km²).

FIGURE 57. Diagram showing measurements performed on a typical Gulf Coast fault compartment. Symbols are defined in the text (p. 77).

FIGURE 58. Histograms of size and shape parameters of the Wilcox trend.

FIGURE 59. Histograms of size and shape parameters of the Frio trend.

TABLE 1. Summary by sector of mean, 10th, 50th, and 90th percentiles for size and shape parameters, fault compartments of the Texas Gulf Coast.

Sector no.	No. blocks	AREA				DEPTH				AZIMUTH (degree)			
		Ave.	Md ₁₀	Md ₅₀	Md ₉₀	Ave.	Md ₁₀	Md ₅₀	Md ₉₀	Ave.	Md ₁₀	Md ₅₀	Md ₉₀
WILCOX TREND													
1	17	9.75	0.85	8.25	30.3	5,600	3,270	5,550	8,330	19	-1	14	67
3	51	7.79	1.23	4.13	14.9	7,810	6,410	7,613	9,595	50	34	51	65
5	36	14.80	2.8	9.0	37.1	7,730	6,760	7,900	8,850	55	39	56	69
7	22	8.50	1.07	5.0	16.8	8,670	5,770	9,300	9,980	67	39	63	92
9	9	17.39	0.9	9.5	70.0	7,710	4,800	8,350	9,200	73	58	73	91
All Wilcox	135	10.66	1.39	5.96	29.6	8,120	5,750	7,880	9,590	—	—	—	—
FRIO TREND													
4	37	6.95	0.93	3.43	16.3	6,170	3,575	6,950	7,730	30	-3	28	61
6	150	10.59	0.79	4.3	27.5	7,880	6,650	8,030	8,975	67	30	67	105
8	204	8.94	0.67	3.55	22.6	9,030	7,330	8,920	10,740	62	15	61	108
10	42	7.94	0.47	4.25	14.8	8,410	7,510	8,350	9,340	55	18	55	107
All Frio	433	9.24	0.83	4.13	22.5	8,328	6,800	8,480	10,260	—	—	—	—
11	9	6.81	1.5	4.5	16.0	5,320	4,800	5,520	5,800	54	39	56	63
ALL BLOCKS	577	9.54				8,233							

Sector no.	ELONGATION				OBLATENESS				CURVATURE							
									Positive				Negative			
	Ave.	Md ₁₀	Md ₅₀	Md ₉₀	Ave.	Md ₁₀	Md ₅₀	Md ₉₀	Ave.	Md ₁₀	Md ₅₀	Md ₉₀	Md ₁₀	Md ₅₀	Md ₉₀	
WILCOX TREND																
1	9.00	2.85	7.25	24.3	0.47	0.28	0.40	0.83	+2.6	1.91	7.08	83.2	-0.19	-2.0	-75.9	
3	6.35	2.78	5.23	10.9	0.59	0.42	0.53	0.80	-1.52	1.17	4.47	17.0	-0.54	-7.08	-70.8	
5	7.99	4.05	5.67	15.4	0.74	0.52	0.67	0.98	+1.87	0.96	2.82	14.5	-0.29	-2.61	-5.82	
7	7.12	2.40	6.50	11.8	0.87	0.56	0.69	1.30	+10.9	3.55	11.8	56.2	-1.48	-6.07	-17.0	
9	6.67	4.45	6.33	12.1	0.72	0.60	0.71	0.92	+4.20	0.18	3.98	23.0	-0.09	-11.2	-12.0	
All Wilcox		7.27	2.1	5.84	13.1	0.67	0.41	0.62	0.95	+2.31	1.15	5.80	21.9	-0.47	-5.16	
FRIO TREND																
4	4.90	2.06	3.73	8.3	0.80	0.56	0.72	1.00	+6.07	0.66	15.8	69.2	-1.12	-10.7	-42.2	
6	5.02	2.29	4.26	9.3	0.70	0.48	0.66	0.95	+0.56	1.77	10.7	35.0	-0.63	-11.7	-39.8	
8	5.54	1.86	4.45	10.3	0.80	0.53	0.72	1.20	+1.12	1.49	11.2	40.7	-2.22	-13.3	-29.0	
10	3.75	1.35	3.6	6.3	0.72	0.52	0.66	0.92	-6.48	2.29	11.2	43.7	-1.12	-18.3	-44.7	
All Frio	5.13	1.96	4.66	9.2	0.76	0.51	0.71	0.97	+0.61	1.72	11.47	39.6	-1.66	-13.18	-39.7	
11	5.06	3.2	4.3	9.3	0.66	0.50	0.65	0.82	-2.45	1.41	9.44	11.2	-5.25	-6.3	-36.0	
ALL BLOCKS	5.63				0.74				+1.0

FIGURE 60. Plot of cumulative percentage of areas accounted for by blocks of less than a given area, Wilcox and Frio trends. Exponential models are also shown.

mapping must filter out these small blocks. Therefore, we attempted to fit the observed distribution with exponential and hyperbolic models. Exponential models give a good fit for the main body of blocks; they have an overcount of blocks less than 1 mi and an undercount of large blocks.

For the Wilcox,

$$n = (18 \pm 2) \exp [-(0.12 \pm 0.03)A].$$

For the Frio,

$$n = (91) \exp [-(0.22 \pm 0.01)A].$$

These give a reasonable fit. However, when cumulative functions with respect to area are plotted (fig. 60), it is evident that these models predict only about half the total fault compartment area with any accuracy. The remaining area lies in a few large blocks, which are not accounted for in the aforementioned model.

Elongation shows a skewed normal distribution. In part, this is caused by the virtual absence of elongations of less than unity. However, this skewness is expected in the following conceptual models.

Oblateness has a roughly normal distribution in both fault compartment trends. The value of oblateness lies between the diamond and rectangle shapes.

Curvature yields a histogram that aids in choosing a fault compartment model. Only the log of the absolute value of curvature can be conveniently plotted; positive curvatures are above the line and negative curvatures below the line (figs. 58 and 59). In this presentation, both trends show a peak of both positive and negative values at about 10^{-5} , Frio curvatures being somewhat larger and Wilcox somewhat smaller; the graph suggests a bell shape. This bimodal curvature pattern may be related to the specific arrangement of growth-fault compartments.

Models

According to the results of the earlier area studies, the growth-fault compartments lie between major growth faults within a growth-fault trend. The ends of the blocks are formed either by convergence of the two major faults or, more commonly, by smaller cross faults. Two models of this population can be tested: a parallelogram model and a trapezoid model (fig. 61).

In the parallelogram model, the parallel cross faults connect major faults lying a distance h apart. They are oriented at an angle θ to the major fault. The measured long axis is inclined at an angle γ to the major faults. For this model, zero curvature is predicted.

The trapezoid model places the cross faults at an angle θ to parallel major faults. Cross faults alternate in orientation, yielding a series of complementary trapezoids. The long axis of this model compartment lies along one of the major faults. For such a model, the absolute curvature is a finite value depending on ΔC and a_1 . This model applies only when the short side of the trapezoid exists, that is, when the following validity criterion is met:

$$\cot \theta \leq \frac{1}{2} E.$$

These models can be tested against the acquired data (table 2). The trapezoid model is valid for most of the blocks in all sectors except sector 1 (South Texas Wilcox), where sample size is small. Angles of cross faults

- a. PARALLELOGRAM: $E(\text{elongation}) = 1/\tan \gamma$
 $\Omega(\text{oblateness}) = E(\sin \gamma \cos \gamma - \sin^2 \gamma / \tan \theta)$
 $K(\text{curvature}) \equiv 0$
 $\tan \theta = \sin \gamma \cos \gamma / (\cos^2 \gamma - \Omega)$

- b. TRAPEZOID: $E = a_1 / \Delta c$
 $\Omega = 1 - 1/(E \tan \theta)$
 $K = 1/[\Delta c(E^2 + 1)]$
 $\theta = \tan^{-1} [1/\{E(1 - \Omega)\}]$
Valid only if $\cot \theta \leq 1/2E$

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FIGURE 61. Parallelogram and trapezoid models of fault compartments.

determined by the two methods are similar, both showing higher angles in the Frio than in the Wilcox. This is probably an artifact; the angle values are unlikely to be physically significant. The major difference between the models is the zero curvature predicted from the parallelogram model versus the bimodal positive and negative curvature predicted from the trapezoid model. The bimodal curvature is in fact observed, which is a strong endorsement of the trapezoid model

for the main compartment populations. Indeed, no other simple model yields evenly matched positive and negative curvature distributions.

The large blocks that skew the area distributions may be blocks located between groups of growth faults, such as the Pleasant Bayou compartment. This is a different population entirely and not covered by the aforementioned models.

TABLE 2. Cross-fault angles and validity tests for the parallelogram and trapezoid models as applied to Wilcox and Frio fault compartments.

Sector no.	No. blocks	TRAPEZOID MODEL		PARALLELOGRAM MODEL	
		Validity (%)	Angle ave. (degree)	Validity	Angle ave. (degree)
WILCOX TREND					
1	17	23.5	18.7	all	12
3	51	58.8	28.8	all	22
5	36	85.7	35.4	all	27
7	22	81.8	31.5	all	51
9	9	100	32.6	all	30
FRIO TREND					
4	37	91.9	50.1	all	51
6	150	80.7	41.7	all	36
8	204	79.9	42.9	all	46
10	42	88.1	50.1	all	49
Total Wilcox	135	67	32		
Total Frio	433	82	44		

Significance of Analysis

Statistical analysis of regional fault compartment data confirmed and extended the distinction of discrete Wilcox and Frio structural styles. The Wilcox style of growth faulting consists of a bundle of nearly straight, closely spaced faults showing little flattening with depth (reaching a décollement plane deep in the Mesozoic section). Mobilization of shale ranges from insignificant (De Witt area) to substantial (Zapata area). This fault style creates fault compartments that are highly elongate, gently curved, and of uniform size. The Frio style of growth faulting consists of several major sinuous faults having moderate flattening with depth, possibly flattening into a regional décollement at 20,000 to 25,000 ft (6,000 to 7,500 m); much mobilized shale is in diapirs and ridges. This style creates fault compartments that are more equidimensional than the Wilcox and have a wide range of sizes and substantial curvature. The influence of salt tectonism was surprisingly

small in the Frio trend but is strong in the Wilcox trend, where sector 7 appears to have a character similar to that of the Frio trend. However, this is mostly an artifact of mapping difficulties, as shown at Katy (Ewing, 1983).

The distribution of fault compartment sizes and shapes has not been determined for areas of shallow décollement such as the South Texas Vicksburg fault zone or the offshore Brazos Ridge fault zone.

Eventually, size and shape data for fault compartments may be matched by size and shape data for sand bodies and sand-body composites formed under various depositional settings. Then the two could be statistically combined to yield a Monte-Carlo-type estimate by sector and trend of the number and size of reservoirs that might yield oil, gas, or geopressured water, and by the percentage of these reservoirs that have one, two, or more stratigraphic boundaries. In this process, data on elongation, area, and azimuth will be especially important.

CONCLUSIONS

From subsurface geological and seismic study of selected areas in the Wilcox and Frio growth-fault trends of the Texas Gulf Coast, some generalizations can be made about the nature and variability of growth faults and fault compartments.

In all areas, structural deformation due to growth faulting was greatest in the early stages of shelf-margin progradation, and has created many dip-reversed compartments, shale ridges, and shale domes. Postprogradation activity on growth faults was comparatively minor, creating large, gentle rollover anticlines. Salt deformation, by contrast, appears to have been most active after shelf-margin progradation and has deformed the structures because of growth faulting.

The Frio and Wilcox fault trends, taken as a whole, show distinct differences, indicated both by interpretation of the study areas and by regional analysis of fault compartment shapes. Frio faults are generally more sinuous and are more widely spaced than Wilcox faults; consequently, Frio fault compartments show less elongation and higher absolute curvature.

Most Frio growth faults have a similar geometry, showing substantial rollover and dip reversal, expansion of section, and moderate flattening of fault zones with depth.

However, at Sarita, a Vicksburg-style low-angle growth-fault décollement occurs in the Frio. Wilcox faults at and northeast of the Live Oak area have little rollover, moderate expansion of section, and little or no flattening with depth. Wilcox faults in South Texas, by contrast, form narrow bands over major shale ridges and adjoining shale-withdrawal basins.

The details of growth-fault geometry and timing are intimately related to the sedimentation history of each area. Thus, general models of growth-fault geometry and growth must be applied with caution and may be of only limited usefulness.

The finding of large geothermal reservoirs in the geopressed zone depends on the favorable intersection of large-volume, high-quality sandstone bodies and large-area fault compartments. Wilcox sandstones tend to be dip-elongate, whereas fault compartments are highly strike-elongate; the probability of large reservoirs is consequently low. Frio sandstones are of mixed geometry, and fault compartments are larger and more equant, suggesting an increased chance of finding large reservoirs. Typical structural geometries of these reservoirs are dip-reversed compartments and withdrawal basins owing to salt or shale mobilization.

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