EFFECT OF HYDROCARBON PRODUCTION AND DEPRESSURIZATION ON SUBSIDENCE AND POSSIBLE FAULT REACTIVATION: PORT ACRES–PORT ARTHUR FIELD AREA, SOUTHEAST TEXAS

2001–2002 Annual Report

by

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ABSTRACT

Subsidence has been extensive in the coastal area of southeast Texas. Despite enormous hydrocarbon production in the area, however, most subsidence has been attributed more to regional shallow groundwater withdrawal than to hydrocarbon production. The impact of hydrocarbon production on subsidence can be accurately quantified only where the effects of groundwater withdrawal are minimal. The Port Acres and Port Arthur field area satisfies this requirement.

More than 380 Bcf of gas has been produced from the Port Acres and Port Arthur field area. Pressure in the Hackberry reservoir declined from an original 9,000 psi to less than 3,000 psi by the 1970's, then to less than 2,000 psi by the 1980's. The pressure drop from 9,000 to 1,000 psi could produce a maximum subsidence of 6 percent at reservoir depth. Assuming an average gas column of 50 to 120 ft, estimated compaction of the Hackberry reservoir is 2 to 5 ft (0.61 to 1.63 m), which is consistent with reported surface subsidence.

INTRODUCTION

In coastal southeast Texas, land subsidence has been extensive, although severe only in the Houston–Galveston area. Despite enormous oil and gas production from Frio and Miocene formations, most land subsidence and surface faults in the area have been attributed more to regional shallow groundwater withdrawal than to hydrocarbon production (Kreitler, 1976; Verbeek and Clanton, 1981; Holzer and Bluntzer, 1984; Gabrysch and Coplin, 1987). Holzer and Bluntzer (1984) showed that hydrocarbon production had caused an additional 0.1 to 0.2 m of local subsidence near some oil and gas fields.

The impact of hydrocarbon production on subsidence and fault reactivation can be accurately quantified only where the effects of groundwater withdrawals are minimal. The Port Neches field area, Orange County, Texas, which satisfies this prerequisite, was studied by Morton and others (2001) and Wang and Nance (2002). This year we extended these studies to the neighboring Port Acres–Port Arthur field area, where groundwater withdrawals are also insignificant.

DATA COLLECTION

Direct measurements of subsurface subsidence, such as casing-collar surveys and extensometer measurements, are valuable but rarely available for old oil and gas fields. Land subsidence may, however, be correlated with hydrocarbon production data and reservoir pressure history where direct measurements of subsurface subsidence and fault movements are unavailable. Geologic and engineering data for Port Acres and Port Arthur fields were collected from Railroad Commission of Texas (TRRC) files, scout tickets, Petroleum Information/Dwight's database, IHS (International Energy Group) data, Bureau of Economic Geology files, and the published literature.

Databases for Port Acres and Port Arthur fields have been compiled, and table 1 summarizes the number of oil and gas reservoirs, wells, and completions. Pressure data are available as either bottom-hole or wellhead shut-in pressure for primary producing reservoirs in the lower Hackberry. As discussed by Wang and Nance (2002), cumulative production data vary significantly between Petroleum Information/Dwight's database and TRRC files.

Table 1. Inventory of reservoir types, wells, and completions.

	Port Acres	Port Arthur
Oil reservoirs	4	1
Gas reservoirs	13	18
Wells	56	17
Completions	78	31

GEOLOGIC SETTING

Port Acres and Port Arthur fields are located in Jefferson County, Texas (fig. 1). Updip Port Acres field is separated from Port Arthur field by a large normal fault having more than 300 ft (>91 m) displacement (fig. 2). More than 380 billion cubic feet (Bcf) of gas has been

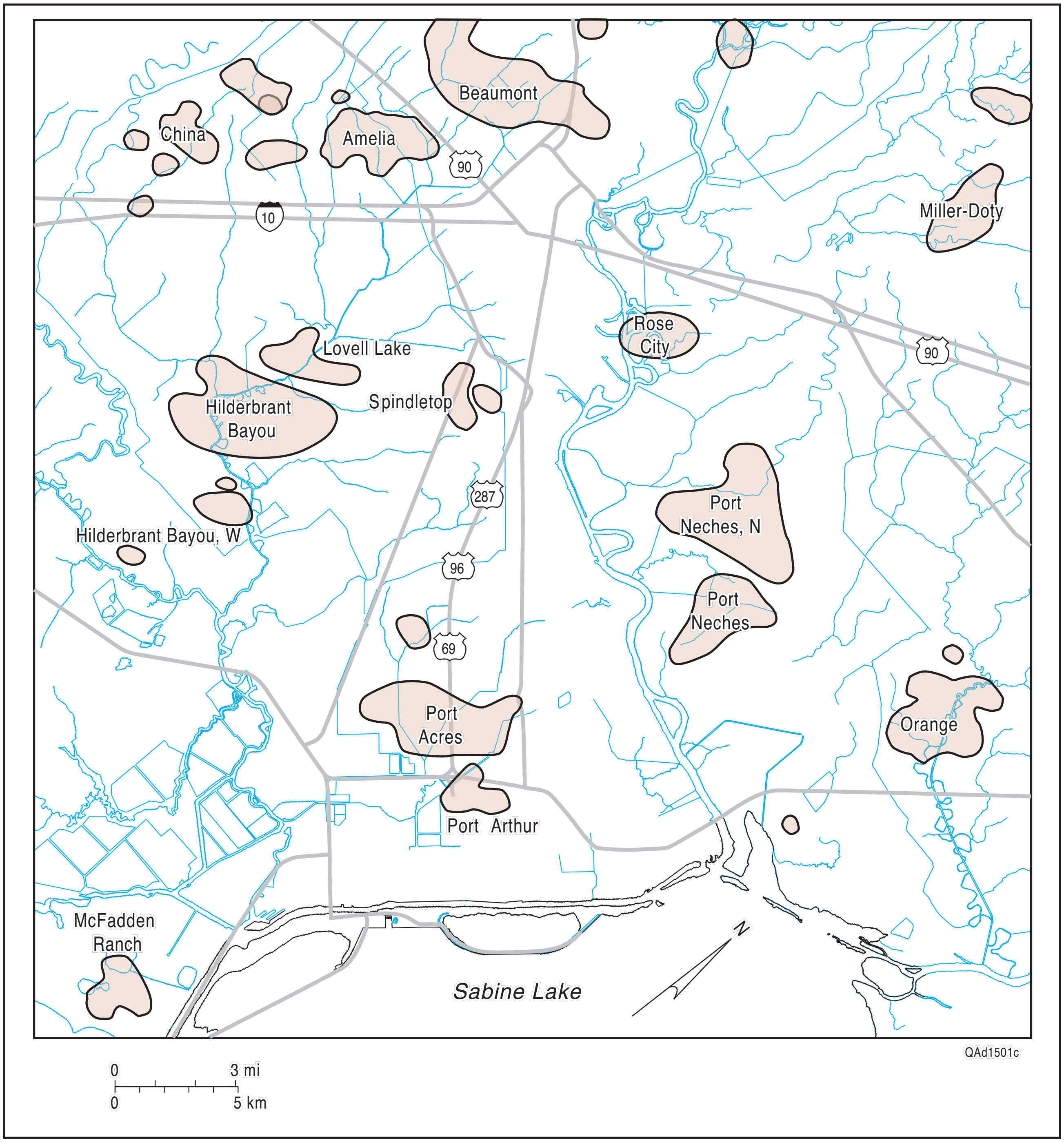

Figure 1. Oil and gas fields in Port Arthur and Beaumont area.

produced from Miocene to Vicksburg formations in these fields, with more than 310 Bcf of gas being produced from Port Acres field (the lower Hackberry member being the largest producing reservoir). The lower Hackberry sandstone in the Port Acres–Port Arthur field area (fig. 3)

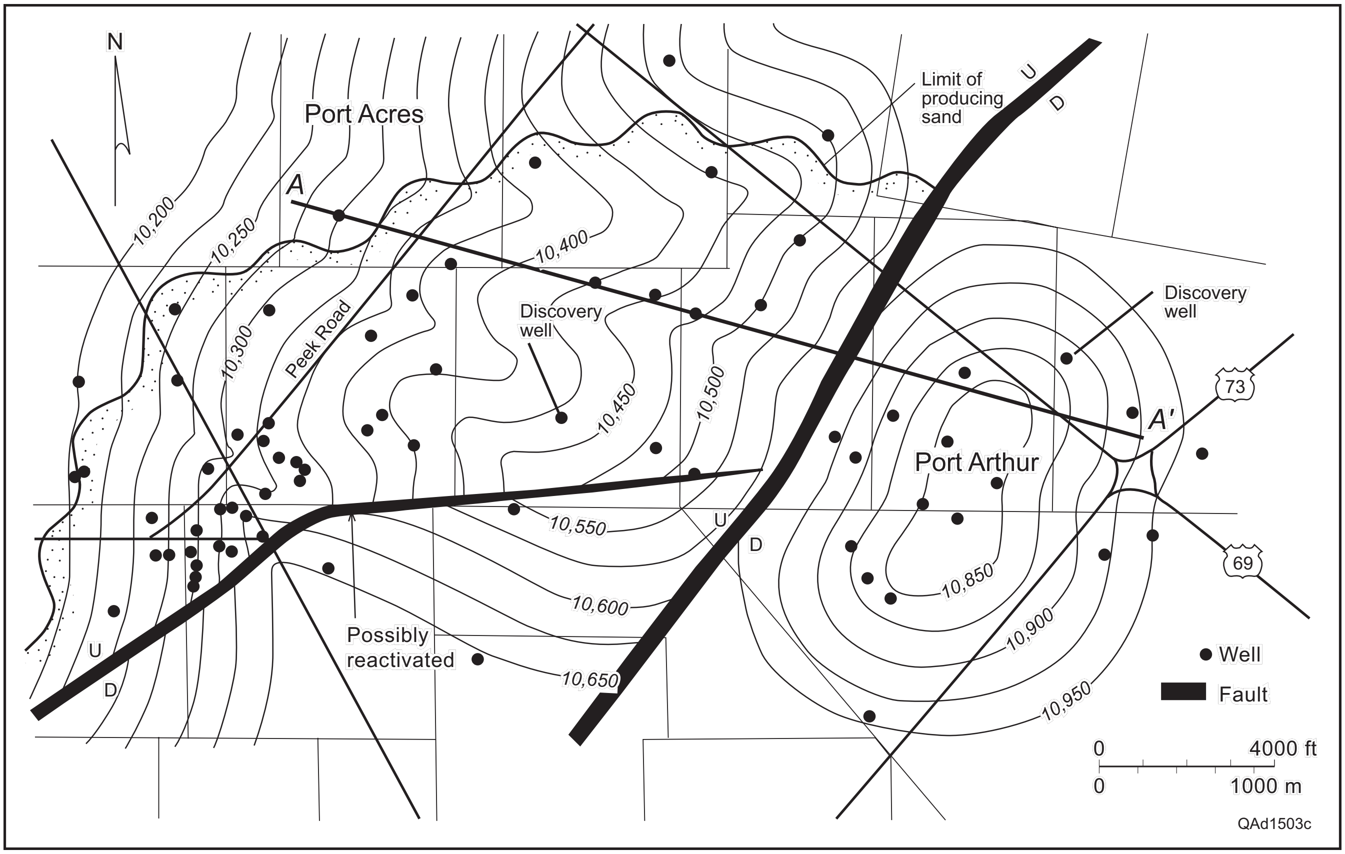

Figure 2. Structure map of Hackberry reservoir, Port Acres and Port Arthur field area. Modified from Halbouty and Barber (1962).

comprises as much as 600 ft (183 m) of stacked submarine channel sands (Morton and others, 1983; Ewing and Reed, 1984). Producing reservoirs are high-quality sands that have an average porosity of around 30 percent and permeability values ranging from 150 to 1,500 md (table 2).

Port Acres field produces mainly from the uppermost two lower Hackberry sands, and Port Arthur field produces from numerous small gas reservoirs overlying large aquifers (fig. 3). Figure 4 shows that the main Port Acres gas reservoir pinches out from southwest to northeast, with a net pay varying between 0 and 140 ft.

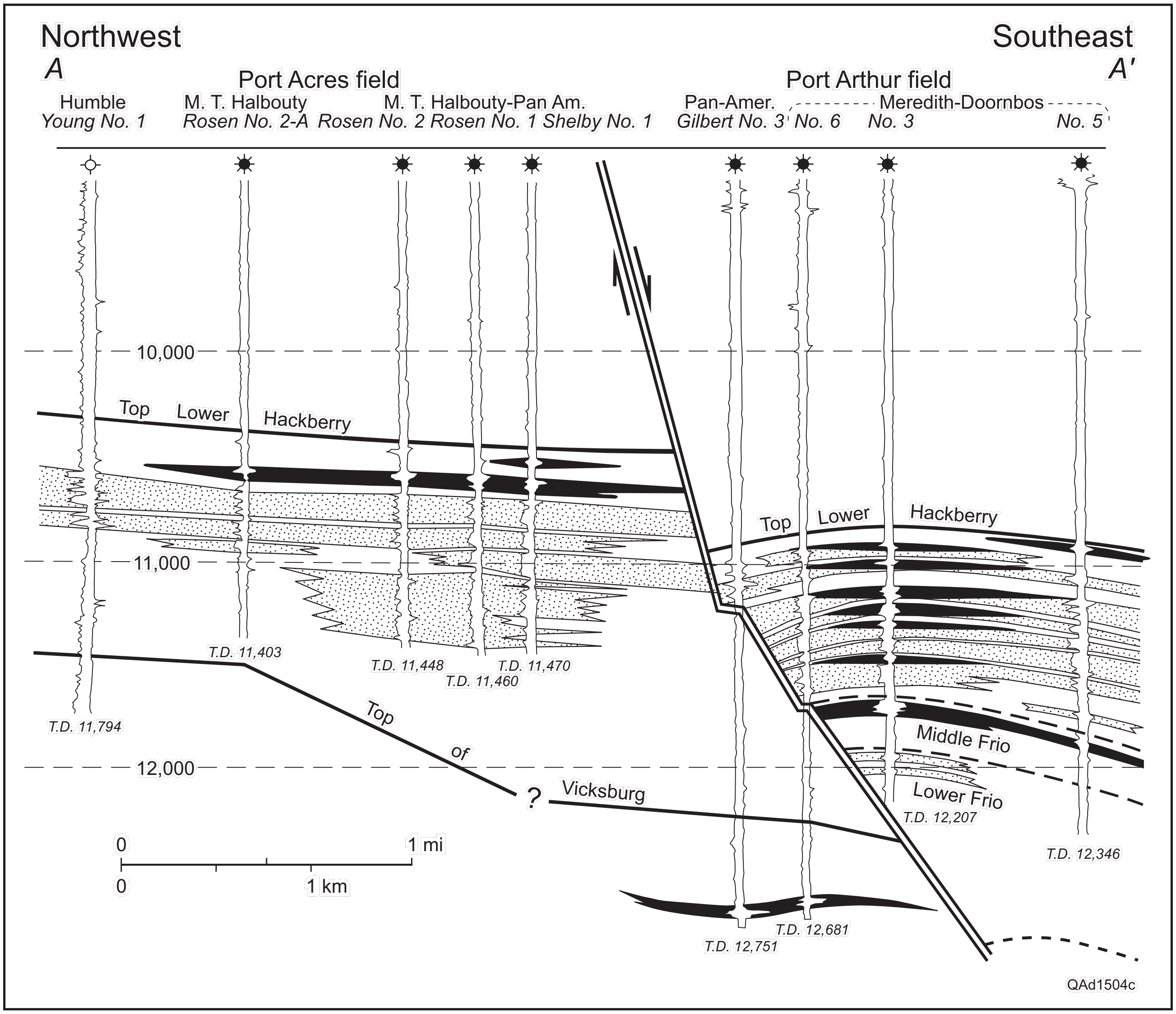

Figure 3. North-south structure cross section of the lower Hackberry reservoir, Port Acres and Port Arthur field. Modified from Halbouty and Barber (1984).

Table 2. Reservoir parameters of Port Acres and Port Arthur (Hackberry) reservoirs.

Field name	Port Acres	Port Arthur
Reservoir name	*Lower Hackberry*	*Lower Hackberry*
HC type	Gas	Oil and gas
Discovery year	1957	1958
Depositional system	Submarine fan[1]	Submarine fan[1]
Trap type	Stratigraphic	Structural/Stratigraphic
Formation	Frio	Frio
Top depth (ft)	–10,360	–10,822
GOC (ft)		
WOC (ft)		Multiple
Initial pressure (psia)	9,015	9,000–10,000
Drive mechanism	Depletion	WD
Net gas (oil)-sand thickness (ft)		50–150[3]
Porosity (%)	29– >120[2]	30–32.8
Internal acoustic velocity (υS/ft)	8,200[4]	8,500[4]
Permeability (md)	150–400	60–1,500
Water saturation (%)	26.6	
Water salinity (mg/L)	82,000–84,000[4]	
Gas condensate (°API)	48–52[4]	48–52[4]
Gas gravity	0.626[4]	0.646[4]

[1]Ewing and Reed, 1984
[2]Halbouty and Barber, 1962
[3]Gregory and others, 1983
[4]Morton and others, 1983

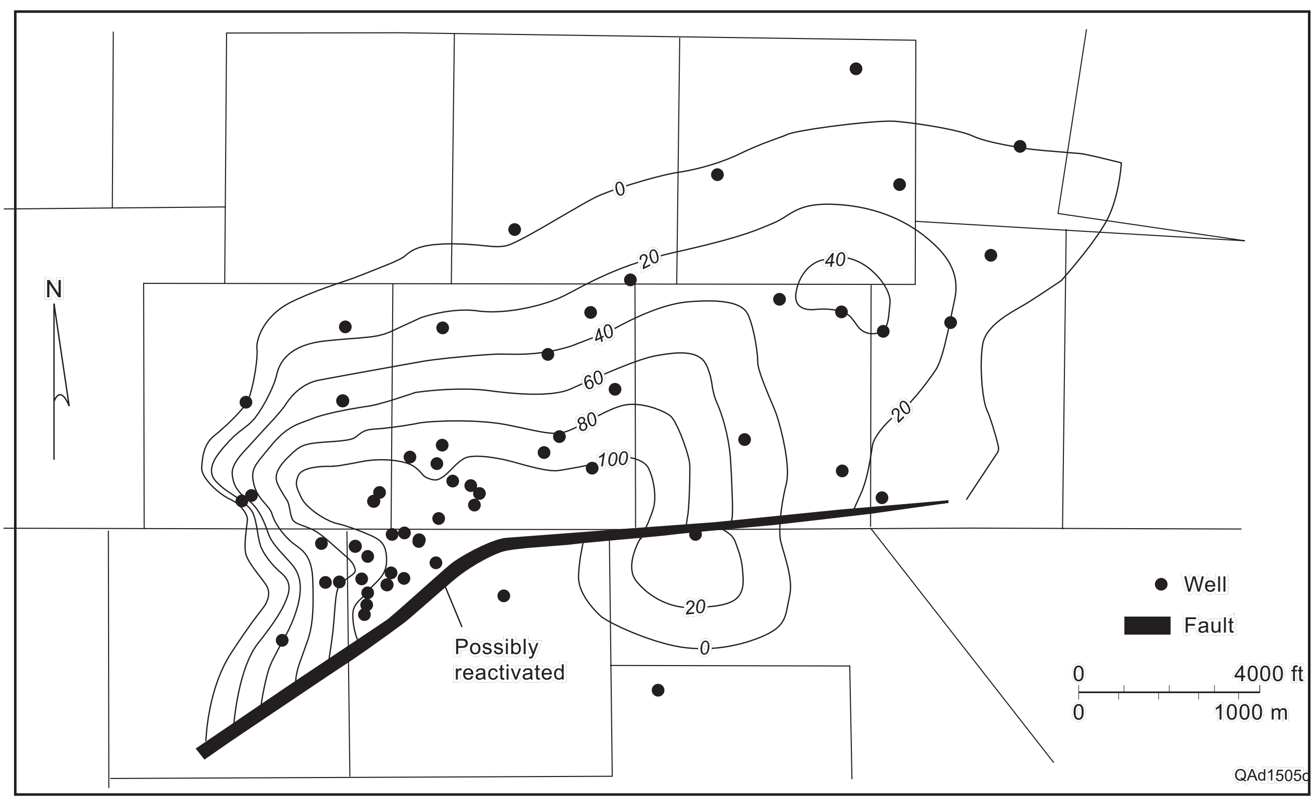

Figure 4. Isopachous map of the net Hackberry gas sand, Port Acres field. Modified from TRRC Docket No. 3-64956, 03/18/75.

PRODUCTION AND PRESSURE HISTORIES

Port Acres field was discovered in 1957, and Port Arthur field in 1958. There are more than 30 producing reservoirs (tables 3 and 4) from the Miocene to the Vicksburg in Port Acres

Table 3. Oil and gas reservoirs in Port Acres field.

Field name	HC type	Discovery year	Depth (ft)
Port Acres North (6000)	Gas		
MARGINULINA 3	Gas	7/3/1985	8636
Frio 1	Gas		
Frio 1-A	Gas		
Frio 5	Gas	8/6/1958	9184
Hackberry 9,500	Gas		
Hackberry 9,600	Gas		
Hackberry 10000	Gas	2/11/1961	10725
Hack. Lo. 10,450	Gas		10450
Hack. Lo. 10,600	Gas	4/17/1972	10316
Lower Hackberry	Gas	8/18/1957	10625
Port Acres South (Hackberry)	Gas		
Port Acres Southwest (Hackberry)	Gas		
Frio 1	Oil		
Frio 1-A	Oil		
Hackberry 9,500	Oil		
Hackberry 10,000	Oil		

Table 4. Oil and gas reservoirs in Port Arthur field.

Field name	HC type	Discovery year	Depth (ft)
MIOCENE 6300	Oil	5/22/1996	6,317
A-1	Gas	12/1/1959	10,946
A-2	Gas	9/4/1959	10,925
B	Gas	4/17/1967	
-B- STRINGER UPPER	Gas	3/18/1966	11,003
B-1	Gas	6/28/1962	11,026
B-2	Gas	5/20/1959	11,077
C	Gas	5/18/1959	11,136
D	Gas	2/29/1960	11,218
-D- UPPER STRINGER	Gas	5/1/1975	11,208
E	Gas	4/1/1959	11,290
E LOWER	Gas	10/31/1967	11,654
F	Gas	7/20/1958	11,350
F-2	Gas	1/20/1996	9,013
G	Gas	3/18/1966	11,470
H	Gas	1/1/1975	11,782
Hackberry	Gas	1958	10,600
Nodosaria	Gas	11/7/1958	12,040
Vicksburg	Gas	11/9/1959	12,674

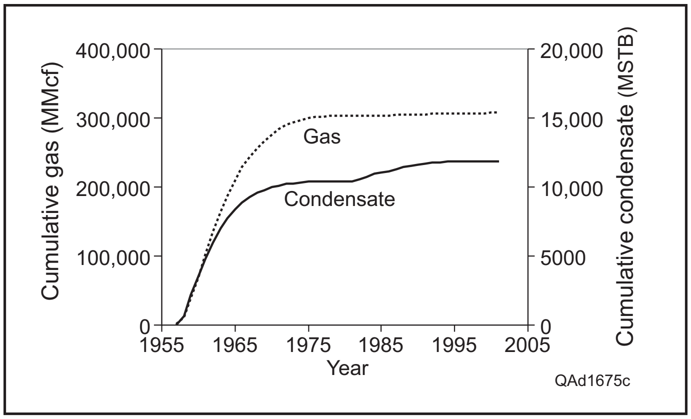

Figure 5. Production history of Port Acres (Hackberry) field.

and Port Arthur fields, with most of the deeper Frio, Nodosaria, and Vicksburg reservoirs being geopressured. Because the main Port Acres gas reservoir is a stratigraphic trap in the lower Hackberry sandstone, the reservoir was produced under depletion drive and water production was not significant. The lower Hackberry gas reservoirs in Port Arthur field, however, were produced under strong water drive.

Figure 5 plots the production history of Port Acres (lower Hackberry) field. Most gas was produced from 1957 through 1970, and the field was substantially abandoned in the 1980's. Average initial bottom-hole pressures of lower Hackberry gas reservoirs were 9,015 psia in Port Acres field and 9,000 to 10,000 psia in Port Arthur field (table 2). Characteristics of initial well pressures (fig. 6) for Port Acres differ significantly from those of Port Arthur. A clear declining trend exists in Port Acres (lower Hackberry) field but not in Port Arthur (lower Hackberry). The decline trend in Port Acres field suggests that the main lower Hackberry gas

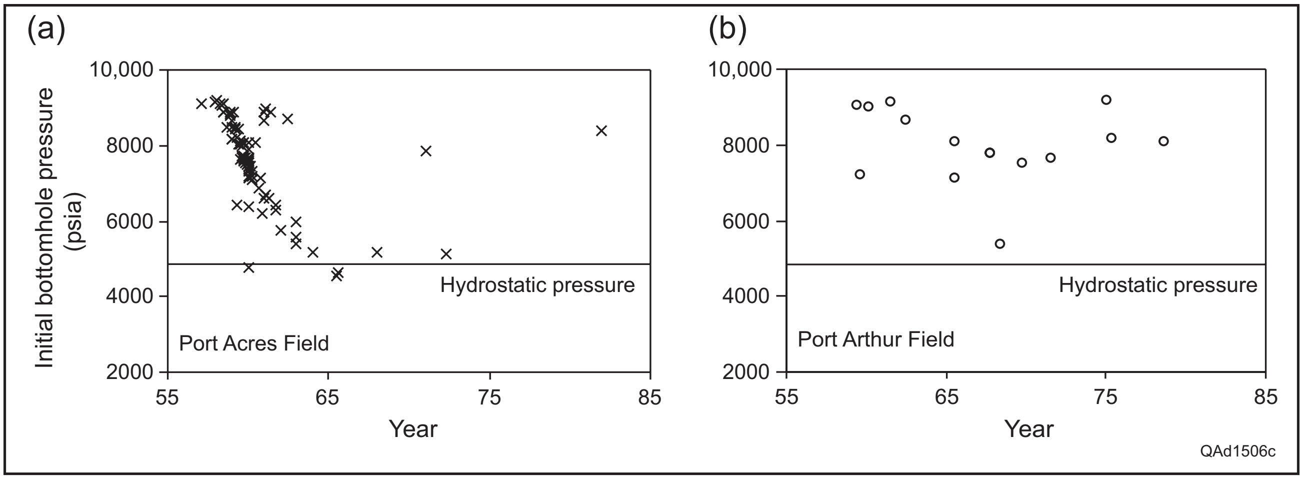

Figure 6. Trends of initial bottom-hole pressure in (a) Port Acres (lower Hackberry) field and (b) Port Arthur (lower Hackberry) field.

reservoir is continuous, but the scatter in initial well pressures in Port Arthur field indicates that lower Hackberry reservoirs are highly compartmentalized.

Figure 7 plots the bottom-hole-pressure histories of wells producing from lower Hackberry reservoirs in Port Acres and Port Arthur fields. In Port Acres, well pressures (fig. 7a to 7c) declined from an initial 9,015 psia to less than 3,000 psia by 1970 and to less than 2,000 psia by the 1980's. Because lower Hackberry reservoirs in Port Arthur field are small and underlain by large aquifers, well pressures (fig. 7d) declined sharply from 9,200 to 4,000 psia in a short period of time and leveled off or declined at a lesser rate when water reached the wells.

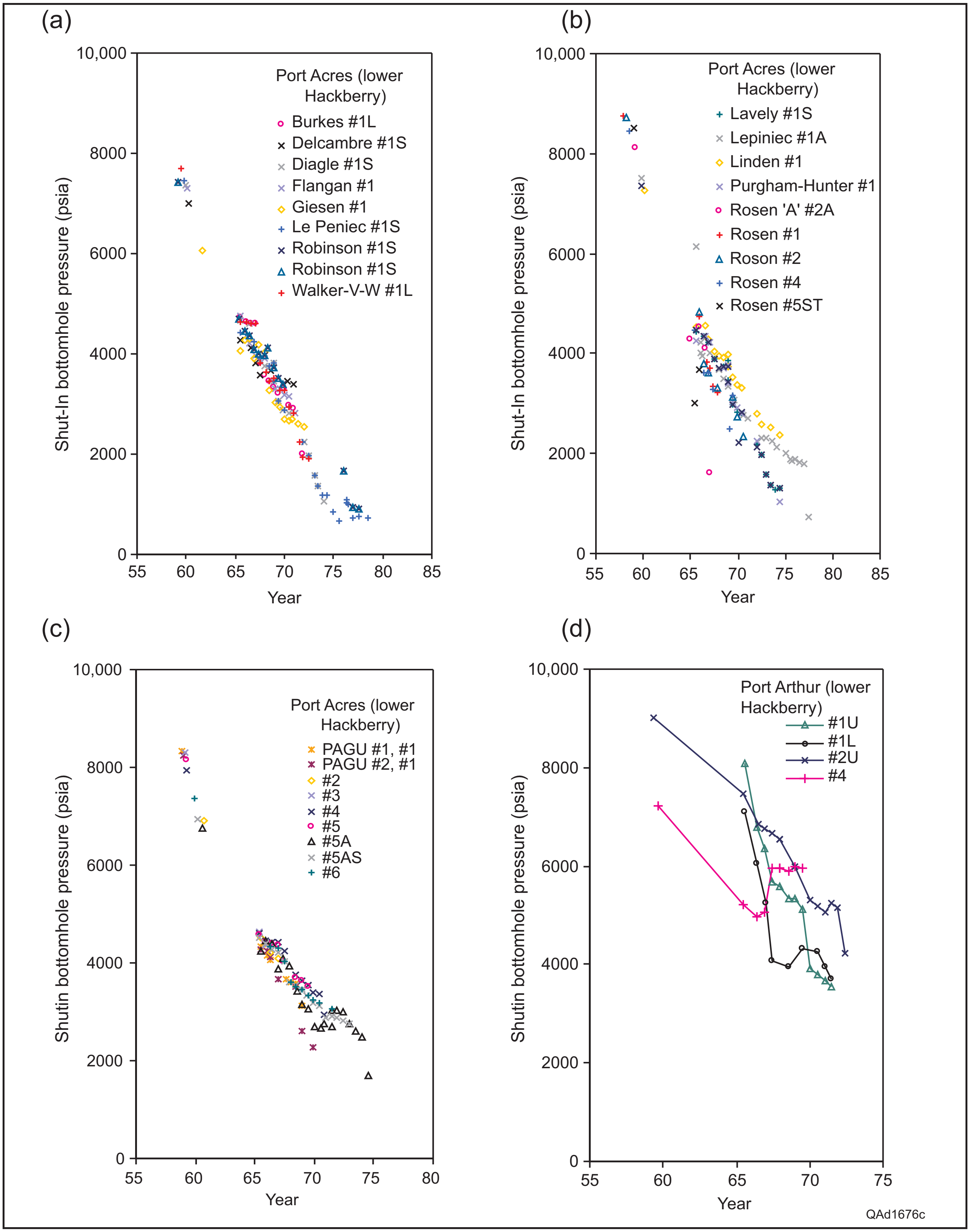

Figure 7. Pressure-decline history of wells, (a) through (c) in Port Acres (lower Hackberry) field and (d) in Port Arthur (lower Hackberry) field.

GRAIN COMPOSITION AND DIAGENESIS

The grain composition of a sandstone and its diagenetic history has a strong effect on the sandstone's state of consolidation in the subsurface. The Frio sandstones in the area of the northern Texas coast are much more mechanically and diagenetically stable than the sandstones along the southern Texas coast (Loucks and others, 1984), resulting in higher reservoir quality at depth along the northern Texas coast.

Mineralogy and Stability

In the areas of investigation, the Oligocene Frio sandstone, of which the Hackberry is a member, is classified as a quartz-rich subarkose (Loucks and others, 1984; fig. 8). The major grain types are quartz and plagioclase-feldspar grains. Quartz grains are mechanically and chemically stable, whereas plagioclase-feldspar grains are relatively mechanically stable but chemically unstable. The higher the percentage of plagioclase-feldspar grains, the more unstable the sandstone becomes during burial.

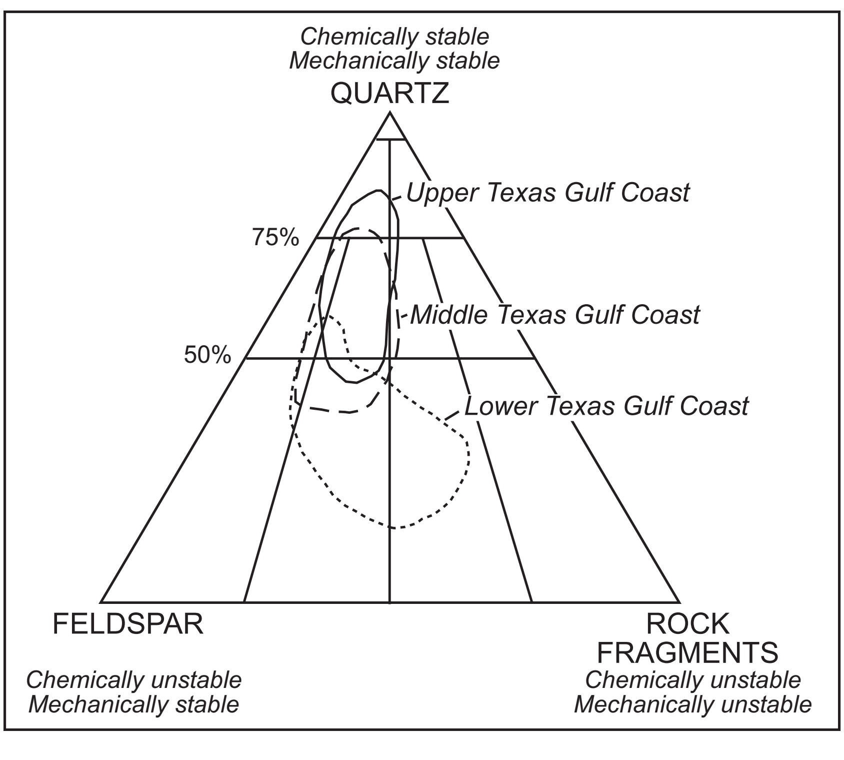

Figure 8. Oligocene Frio sandstone composite along the Texas Gulf Coast.

Effects of Diagenesis on Sandstone Stability

The sandstones within the area of investigation are buried to depths of between 10,000 and 11,000 ft. At these burial depths, the sandstones are consolidated into a relatively rigid framework. The average porosity of 29 percent indicates that the volume of pore space is high, but the grains are still cemented to each other. The quartz grains have quartz-overgrowth cements that connect to other quartz grains, and some carbonate cements also help consolidate the sand grains into a relatively rigid framework.

The plagioclase-feldspar grains undergo dissolution with burial, especially in the depth range of 7,000 to 8,000 ft, forming secondary moldic pores (Loucks and others, 1984; fig. 9). These dissolved feldspars commonly form oversized pore spaces that are outlined by the rim of the former plagioclase-feldspar grain. Microporous kaolinite clay may fill the moldic pores.

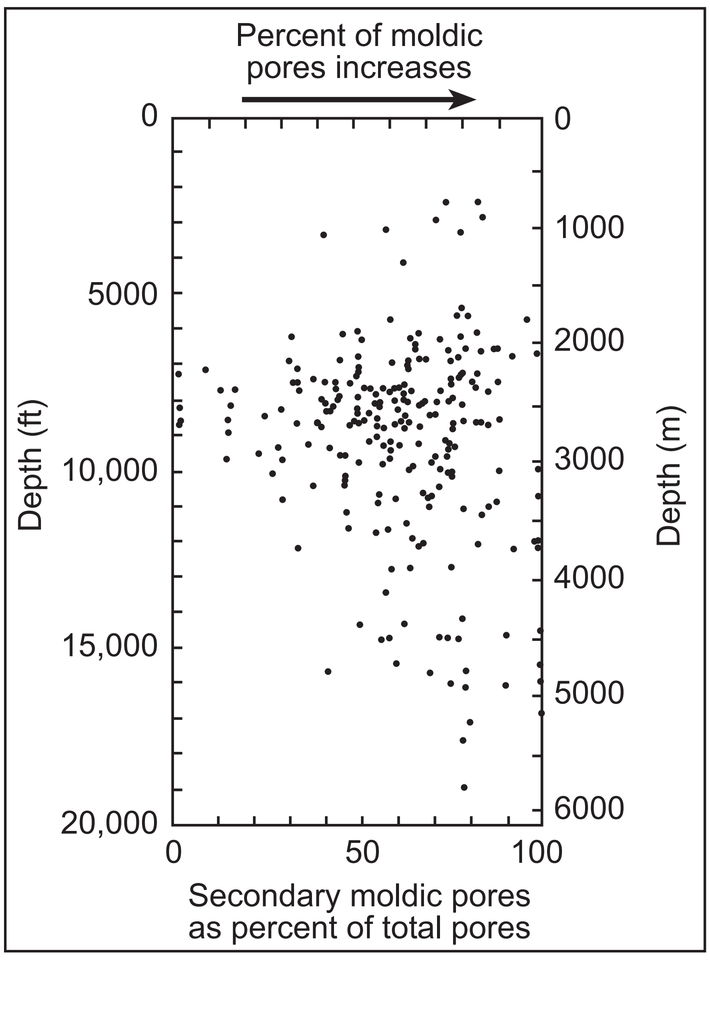

Figure 9. Secondary moldic pores as a percent of total pores vs. depth for Oligocene sandstones.

Pore Network

The pore network of the sandstones in these fields is composed of primary interparticle pores, moldic pores developed from dissolution of plagioclase-feldspar grains, and micropores within kaolinite cement. The high permeabilities in the fields indicate that the interparticle pore space is high because it is the major pore space that contributes to permeability. However, regional data on pore networks collected by Loucks and others (1984) suggests that 50 percent or more of the pore space can be moldic pores at these depths in this area (fig. 9). This observation is important because these moldic pores may be mechanically unstable and prone to collapse.

Compaction

As the sandstones are buried into the subsurface, the grains tend to pack more closely together until a mechanically stable arrangement is attained. Weak cementation will slow compaction and strong cementation will arrest compaction. In the area of investigation, cementation is moderate at best, leaving some of the sandstones friable.

Under normal hydrostatic pressure, sandstone compaction will generally increase with burial. If sandstones enter into an overpressured regime, as they did in the area of investigation, compaction is slowed down or arrested. With continued burial after pressuring, the fluids within the sandstone will help support the grains, preserving a higher percentage of pore space with depth than would be possible under normal hydrostatic burial conditions. This situation is especially important when many of the pore spaces are delicate moldic pores. The overpressuring may allow the moldic pores not to compact as they might under normal pressure conditions.

Possible Effects of Grain Composition and Diagenesis on Compaction

A sandstone in the overpressured zone is essentially undercompacted relative to its depth of burial. Any decrease in pressure will make the sandstone appear out of equilibrium relative to depth. With huge decreases in pressure due to hydrocarbon production, as seen in the area of investigation, compaction of the sandstone would be expected. Compaction within the sandstone would take place by (1) the grains moving closer together where they are not well cemented, (2) microfaulting where grains are partly cemented, and (3) collapse (crushing) of the moldic plagioclase-feldspar grains. The result could be significant lost of pore space and a decrease in sandstone-body thickness. In the more rigid lenses of the sandstone body, small faults may develop. The major question is whether this decrease in sandstone thickness could be translated to the surface or whether it would be accommodated by the less lithified strata above.

Models for Subsidence at the Surface

That compaction takes place in the Hackberry sandstone at depth by production of hydrocarbons is highly probable. Three different processes could explain how this compaction between 10,000 and 11,000 ft translates to the surface. The first process could be related to reactivation of older faults. These older faults are planes of weakness and may move during depressuring of the reservoir. The second and third processes could be related to the Hackberry reservoir compressing, and the units above are subsiding because of the decrease in Hackberry thickness. This potential subsidence could be the result of grain-to-grain movement in the less lithified strata above or small displacements on numerous faults. The numerous small faults may be similar to the results of the “stoping” process seen in carbonate cave collapse. As the cave chamber collapses (a process similar to the compression of the sandstone bed), the unit above collapses by small-scale faulting. Following this collapse, the unit above collapses, and so on. It is questionable whether subsidence (collapse) either by grain-to-grain movement in the less lithified strata above or by numerous small faults (stoping) could translate all the way to the surface 10,000 ft above. Fault reactivation at the surface, which is produced by a few tens of feet of compactional displacement more than 10,000 ft below the surface, is difficult to explain. Perhaps a combination of these three processes translated the subsidence to the surface.

SUBSIDENCE AND FAULT REACTIVATION ANALYSES

Reservoir subsidence and fault reactivation in the Port Acres (lower Hackberry) reservoir might be expected because of its more than 300 Bcf gas production and 7,000 to 8,000 psi pressure decline. Because production is from subsea depths of 10,360 ft, however, a question must be raised about how subsidence of the deeply buried lower Hackberry reservoir could affect the surface landscape.

Surface Subsidence

Ratzlaff (1982) reported as much as 2 ft (0.6 m) of subsidence in the outskirts of Port Acres field and concluded that subsidence was most likely caused by oil and gas production from nearby fields. White and others (1984) observed a 6-ft subsidence at the outskirts of Port Acres field. Subsidence measurements in the field are, however, not available. And yet changes in landscape in the field area can be detected from 1953 and 1978 aerial photos. Figure 10 shows a 1978 aerial photo in which green represents wetland. The black outline indicates the wetland in 1953 (Fisher and others, 1973), and the red line indicates the wetland in 1978. The increase in wetland between 1953 and 1978 coincides with the 300-Bcf gas production in Port Acres field. Although canals have been built to drain water in the area, many local ponds 20 to 50 ft in diameter lie near gas wells today.

Reservoir Compaction and Subsidence Analysis

Reservoir compaction, which induces land subsidence but also increases oil and gas recovery, is referred to as “compaction drive” in the petroleum industry. Figure 11a shows the relationships between formation compressibility and effective stress for unconsolidated, friable, and consolidated sandstones (Yale and others, 1993). Figure 11b shows the relationships between formation compressibility and reservoir pressure for unconsolidated and consolidated sandstones. Note that the formation compressibility of unconsolidated rocks is an order of magnitude higher than that of consolidated rocks. For geopressured, unconsolidated sands,

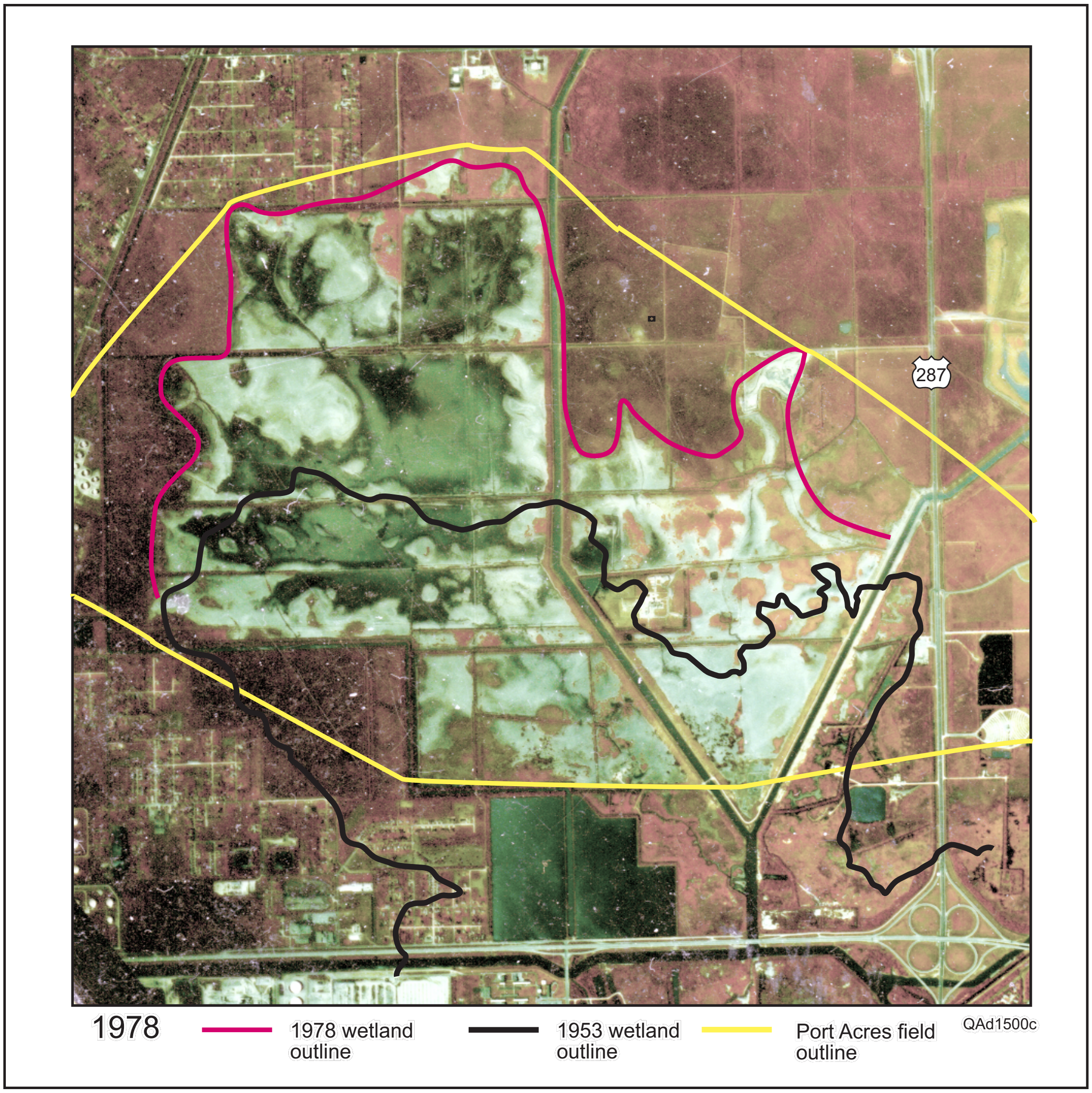

Figure 10. (a) 1978 Aerial photo showing wetlands and (b) change in wetlands in Port Acres–Port Arthur field area from 1953 through 1978.

formation compressibility can be reduced by 25 percent when reservoir pressure decreases from 9,000 to 4,000 psi. Formation compressibility is defined as a function of pore volume:

$$C_f = \frac{1}{V_p}\frac{\partial V_p}{\partial p} = \frac{1}{\phi h}\frac{\partial(\phi h)}{\partial p} \quad (1)$$

$$= \frac{1}{\phi}\frac{\partial \phi}{\partial p} \quad (1a)$$

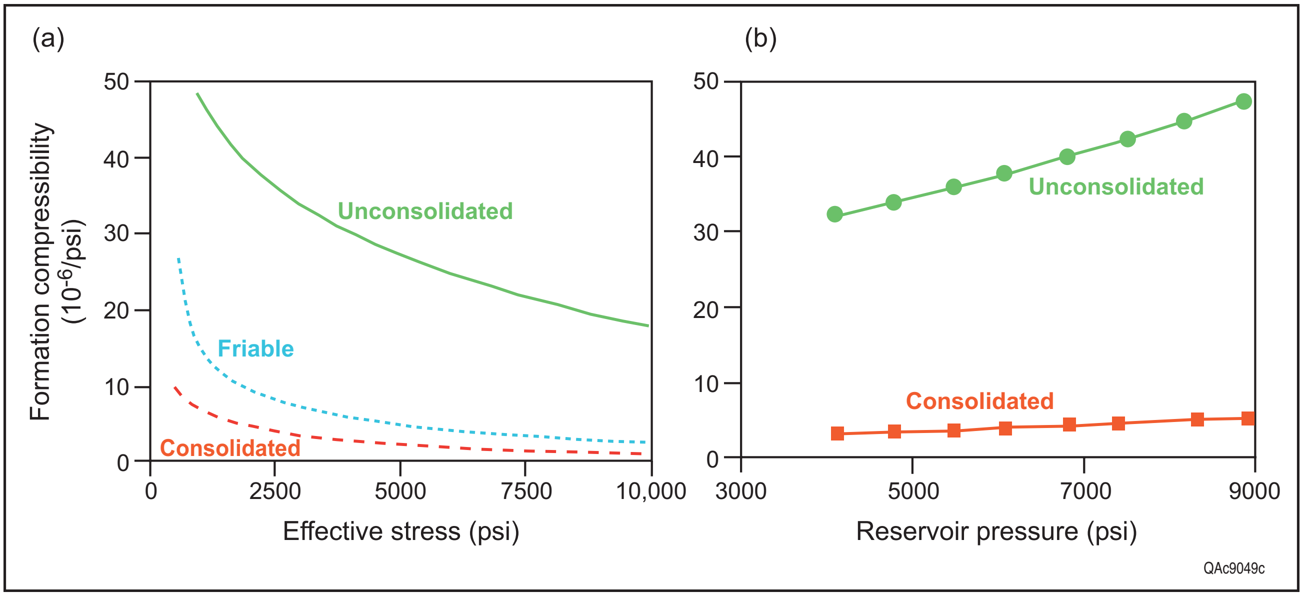

Figure 11. Effect of pressure on formation compressibility: (a) formation compressibility vs. effective stress and (b) formation compressibility vs. pore pressure. From Yale and others (1993).

when h is constant, and solving equation 1 for ϕh by integration yields

$$\phi h = (\phi h)_i e^{c_f (p - p_i)} \qquad (2)$$

where

C_f : formation compressibility in psi^{-1}
V_p : pore volume in ft^3
P : pore pressure in psi
ϕ : porosity
h : reservoir thickness.

When h is assumed to be constant, equation 1 reduces to equation 1a, which is commonly used in compaction-drive analysis (TRRC, Docket No. 3-93626, 1989; Sulak and others, 1991; Yale and others, 1993). Equation 2 can be used to estimate the upper limiting value of reservoir subsidence at a specific reservoir pressure. When reservoir pressure decreases, both porosity and thickness decrease. Net compaction (subsidence) increases with reservoir thickness, formation compressibility, and pressure change.

Even though formation compressibility measurements are not available for the Port Acres (lower Hackberry) reservoir, the porosity reduction of from 29 to 17.5 percent (when

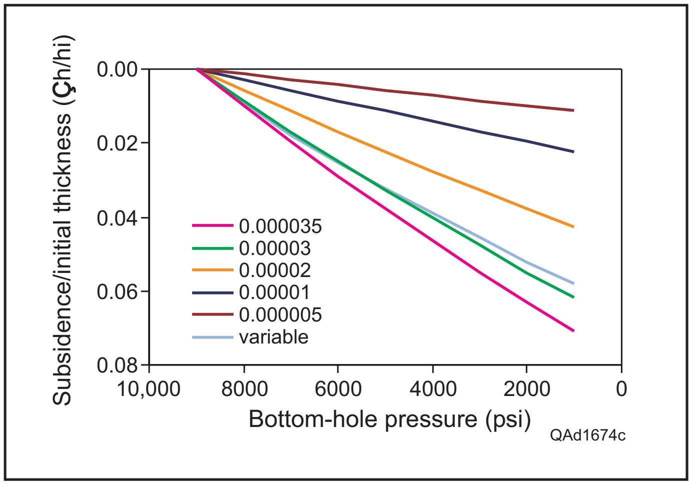

Figure 12. Effect of formation compressibility on reservoir subsidence.

pressure declined from 9,015 psia in 1957 to 1,000 psia in 1979 [TRRC, Docket No. 3-93626, 1989]) was used for estimating the recovery factor of the Snell Lease.

Figure 12 shows the effect of formation compressibility on reservoir subsidence with respect to reservoir pressures in Port Acres (lower Hackberry), using equation 1. Subsidence in figure 12 is represented as percent change in thickness, which is subsidence divided by initial reservoir thickness. Formation compressibility varies from 5×10^{-6} psi^{-1} for consolidated rocks to 35×10^{-6} psi^{-1} for geopressured unconsolidated rocks. Reservoir subsidence increases with formation compressibility. In the case of variable compressibility, we use the data in figure 11b, with formation compressibility varying from 35×10^{-6} at 9,000 psi to 20×10^{-6} at 1,000 psi, and estimate subsidence to be 6 percent at 1,000 psi. Assuming a 50- to 120-ft gas column, the upper limiting subsidence at the top of the Hackberry reservoir was 2 to 5 ft (0.6 to 1.6 m), which is consistent with the range reported by Ratzlaff (1982) and White (1984). The relatively small estimated subsidence at the Hackberry reservoir stems from the gas-producing sands being thin, although the Lower Hackberry Formation in this area is very thick.

Fault-Reactivation Analysis

Figures 3 and 4 show that the thickest part of the lower Hackberry sandstone gas sand in Port Acres field occurs from the central part to the western, structurally high margin along the southern boundary fault. Because this area has been subjected to the largest depletion and subsidence in the field, the adjacent southern boundary fault was most likely reactivated (Fault “B” in fig. 4). Mr. Alvin Chan conducted a fault-reactivation analysis of the Port Acres data (Chan, 2002) using DARS (deformation analysis in reservoir space), which was developed by Chan and Zoback (2002).

As shown by Chan and Zoback (2002), faults can be induced by hydrocarbon production if stress changes follow the path with a slope greater than 0.67 for the normal faulting line (fig. 13). In addition to porosity and pore-pressure data, analysis requires stress measurements from field and laboratory. Minimum horizontal stresses are from minifracs and leak-off tests, and reservoir pore pressures are from shut-in pressure tests. Because field stress data from minifracs, leak-off tests, and RFT’s are unavailable for old fields, such as Port Acres and Port Arthur, we can determine neither the exact path of stresses nor, hence, whether Fault “B” was reactivated (Chan, 2002).

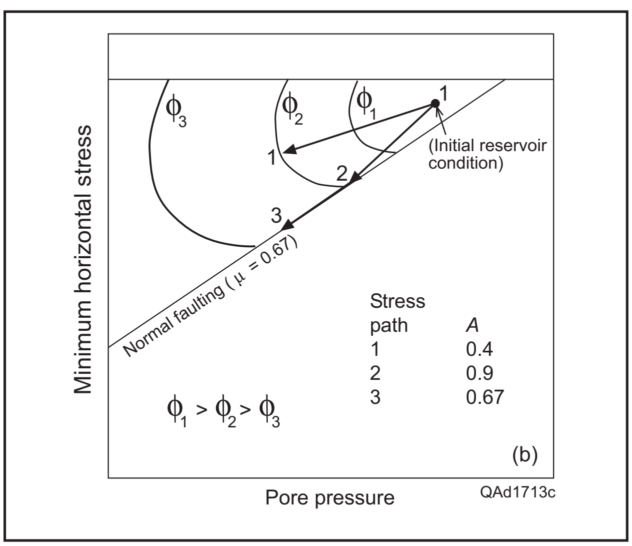

Figure 13. Schematic diagram showing deformation analysis in reservoir space (DARS). Paths 1, 2 and 3 are possible stress loci during reservoir depletion. Path 1 is the path for reservoir depletion without inducing normal faulting. Path 2 and 3 are paths that reservoir will deforms to eventually induce normal faulting. Modified from Chan and Zoback (2002).

SUMMARY

Production-induced subsidence in Hackberry sandstone is strongly related to reservoir compaction and pore collapse, which are functions of porosity, thickness, and degree of depressurization of the reservoir, and diagenesis.

With an estimate of 308 Bcf of gas produced from Port Acres (lower Hackberry) field, the reservoir has been fully depleted from about 9,000 to 1,000 psi. With 29 percent porosity and high formation compressibility, the estimated thickness reduction by compaction is 2 to 5 ft (0.61 to 1.52 m) at the top of the Hackberry for a net-pay thickness ranging from 50 to 140 ft (6.1 to 42.7 m). The 2- to 5-ft (0.61- to 1.52 -m) thickness reduction agrees with the amount of surface subsidence reported by Ratzlaff (1982) and White and others (1984).

Because of the absence of stress data, the exact path of the stress field and the possibility of fault reactivation in the Port Acres field area cannot be determined. Nevertheless, the southern boundary fault “B” in Port Acres field was most likely reactivated because the gas column is thickest and subsidence was greatest near this fault.

ACKNOWLEDGMENTS

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