Overpressure and Hydrocarbon Accumulations in Tertiary Strata, Gulf Coast of Louisiana*

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Search and Discovery Article #41000 (2012)**
Posted August 20, 2012

*This manuscript is the basis of an oral presentation by P.H. Nelson at the 2008 Annual Conference and Exhibition of the American Association of Petroleum Geologists in San Antonio, Texas, titled: "Overpressure, stress gradients, and hydrocarbon accumulations in Tertiary strata, Gulf Coast of Louisiana"

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Abstract

Many oil and gas reservoirs in Tertiary strata of southern Louisiana are located close to the interface between a sand-rich, normally pressured sequence and an underlying sand-poor, overpressured sequence. This association, recognized for many years by Gulf Coast explorationists, is revisited here because of its relevance to an assessment of undiscovered oil and gas potential in the Gulf Coast of Louisiana. The transition from normally pressured to highly overpressured sediments is documented by converting mud weights to pressure, plotting all pressure data from an individual field as a function of depth, and selecting a top and base of the pressure transition zone. Vertical extents of pressure transition zones in 34 fields across southern onshore Louisiana range from 300 to 9000 ft and are greatest in younger strata and in the larger fields. Display of pressure transition zones on geologic cross sections illustrates the relative independence of the depth of the pressure transition zone and geologic age.

Comparison of the depth distribution of pressure transition zones with production intervals confirms previous findings that production intervals generally overlap the pressure transition zone in depth and that the median production depth lies above the base of the pressure transition zone in most fields. However, in 11 of 55 fields with deep drilling, substantial amounts of oil and gas have been produced from depths deeper than 2000 ft below the base of the pressure transition zone.

Mud-weight data in 7 fields show that "local" pressure gradients range from 0.91 to 1.26 psi/ft below the base of the pressure transition zone. Pressure gradients are higher and computed effective stress gradients are negative in younger strata in coastal areas, indicating that a greater potential for fluid and sediment movement exists there than in older Tertiary strata.

Introduction

The nature and ubiquity of overpressured conditions in the subsurface of the Gulf Coast was documented by Dickinson (1953), who (1) showed that overpressuring exists in a belt 35 to 75 mi wide by 800 mi long, extending from the Rio Grande River to the Mississippi Delta; (2) showed that the top of overpressure occurs within a shale-dominated sequence overlain by a sand-dominated sequence; (3) noted a lack of dependence of overpressure upon depth and formation age; (4) mapped the gulfward progression of the top of overpressure from older to younger strata; (5) established values of 0.465 psi/ft and 1.0 psi/ft for normal hydrostatic and lithostatic pressure gradients, respectively; (6) noted that many of the abnormally pressured sand bodies flowed salt water with no oil, but also noted it was probable that solution gas was present in the water; and (7) argued that compaction is the dominant mechanism in creating overpressure.

Papers published since Dickinson's landmark paper (Dickinson, 1953) have substantiated and extended his findings. Morton (1991, p. 519) stated that:

> Because of facies dependency, the regional top of geopressure is expressed as a subparallel series of highs and lows. The upper boundary is depressed beneath sand-rich depocenters and is elevated basinward above massive shales. The top of geopressure represents an important geologic and hydrologic boundary because it controls fluid migration, hydrocarbon accumulation, and diagenetic reactions. In the geopressured zone, sediments are gas prone, fault density increases, fault angles decrease, clay minerals are transformed from smectite to illite, and organic matter matures to form hydrocarbons.

This succinct summary touches on three topics that are pursued in the present paper: (1) the lithologic control on the depth to geopressure and its expression in map form, (2) the relation of the top of geopressure to fluid migration and hydrocarbon accumulations, and (3) conditions within the overpressured zone. The main emphasis of this article is on the second of these topics, with lesser contributions to the first and third. This work was done in support of the oil and gas assessment of Tertiary strata in the Gulf Coast by the U.S. Geological Survey (USGS).

In this study, the relation between the depth of oil and gas reservoirs and the nature of overpressuring in Tertiary formations (Figure 1) of the Louisiana Gulf Coast is reexamined. Rather than proceeding on a well-by-well basis, as in the study of Fertl and Leach (1990), the pressure and production data were aggregated on a field-by-field basis, using a commercial database (IHS Energy Group, 2006) for this purpose. (Note: the effect of temperature on the distribution of hydrocarbon reservoirs is not examined in this study.) The pressure regimes in 91 fields were inspected as a first step and of these, 34 fields (Figure 2, Table 1) were selected for presentation of pressure-depth plots and the depth extents of cumulative production. Eleven fields provided clear evidence of production at depths substantially below the base of the pressure transition zone. Finally, excess pore pressure and effective stress were computed for 7 fields having extensive pressure data below the pressure transition zone.

Pressure Data and Pressure Transition Zones

The three types of pressure data extracted from a commercial data base (IHS Energy Group, 2006) for presentation on pressure-depth plots were pressures measured during drillstem tests, bottom-hole pressures determined during testing and production, and mud weights used in drilling a well. The drillstem-test and bottom-hole pressures, which are generally recorded within limited depth ranges, reflect the zones of production, whereas the mud weights, which are distributed more or less continuously with depth, reflect the pressure conditions anticipated for the next drilling interval.

The pressure plotted from a drillstem test is the greater of the pressures measured in the initial and final shut-in periods. A pressure measured during a drillstem test may be less than true formation pressure, either because of inadequate measurement time or insufficient communication with the formation. It is also possible that the tested interval has undergone pressure reduction due to production in nearby wells.

Bottom-hole pressures are generally not measured but are computed from wellhead pressures. Bottom-hole shut-in pressures accurately measure formation pressure if the test period is sufficiently long. The large number of bottom-hole pressures that are less than hydrostatic pressure is largely attributed to the decline of pressure with production time. All bottom-hole pressures were included in the plots presented herein without any editing. Mud weight, in pounds per gallon (ppg), was converted to an equivalent pressure Pm by Pm (psi) = [mud weight (ppg) / 8.33 (ppg)] × 0.433 (psi/ft) × depth (ft) (1) where 8.33 ppg and 0.433 psi/ft are the density and pressure gradient of fresh water. The number of mud-weight measurements from any given well in a field varies considerably. For example, 208 mud-weight values were recorded in 77 wells in Abbeville field (Figure 3), with most wells contributing only a few mud-weight values, but there was one well that contributed 19 values distributed over a depth range of 3500 to 20,000 ft.

Because a particular mud weight is chosen to control downhole well pressure while drilling, thereby avoiding possible blow-outs, the pressure calculated from mud weight is generally greater than the formation pressure. Mud weight data from an individual well may not represent the true in situ pressure, so an examination of mud weights from a number of wells is the best means for determining the top and base of overpressured regimes (Powley, 1987). For this reason, data from individual wells are grouped by field (Plates 1, 2, and 3). Hence, the equivalent pressures obtained from mud weights are used to define a transition zone in which pressure increases from hydrostatic to overpressured, as shown in the example for Abbeville field (Figure 3) and in the pressure-depth plots in Plates 1, 2, and 3. From inspection of the pressure-depth plots, the following definitions were applied: (1) the top of the pressure transition zone is the depth above which few pressure-depth ratios exceed 0.6 psi/ft (equivalent to a density of 11.5 ppg), and (2) the base of the transition zone is the depth below which few pressure-depth ratios are less than 0.6 psi/ft.

Isolated data points were ignored in selecting the top and base of the pressure transition zone. Other workers have used different criteria. Wallace et al (1981) adopted a criterion of 0.5 psi/ft for mapping the top of overpressure. Harrison (1980) defined the pressure transition zone to be between 0.5 and 0.7 psi/ft, with the top of "hard geopressure" at 0.7 psi/ft. Rather than adopting criteria for a pressure transition zone, Fertl and Leach (1990) examined hydrocarbon production as a function of mud weight ranging from 10.5 ppg (equivalent to 0.55 psi/ft) to 18.0 ppg (0.94 psi/ft) (see Figure 11). Therefore, as defined herein, the top of the pressure transition zone may lie somewhat deeper than the top of overpressure defined by others and the base of the pressure transition zone is roughly comparable to the top of "hard overpressure" as defined by Harrison (1980).

As a result of structural offsets within an oil and gas field, the top of overpressure is encountered at different depths in different wells. The greater the fault displacements across a field, the greater the apparent thickness of the transition zone. In some fields, such as Bayou Sorrel (Plate 2), the transition zone is well defined and is less than 1000 ft thick. In other fields, the transition zone has a large vertical extent and the top and base are poorly defined. For example, Caillou Island, which is a giant field, has a transition zone that is nearly 8000 ft thick, with a few scattered high-pressure points as shallow as 6000 ft (Plate 3).

Pressure within a hydrocarbon reservoir increases with height above the hydrocarbon-water contact due to buoyancy pressure. The contribution of reservoir buoyancy pressure was not accounted for in this study; so some pressures are higher than those due to overpressure alone. This effect could raise the apparent top or bottom (or both) of the pressure transition zone.

SYSTEM	SERIES	GROUP	FORMATION
TERTIARY	PLIOCENE		
	UPPER MIOCENE		
	MIDDLE MIOCENE		
	LOWER MIOCENE		
	OLIGOCENE	Catahoula	Anahuac
			Frio
		Vicksburg	
	EOCENE	Jackson	
		Claiborne	Cockfield
			Sparta
	PALEOCENE	Wilcox	
		Midway	
CRETACEOUS	GULF	Navarro	
		Taylor	
		Austin	
		Eagle Ford	
		Tuscaloosa	
	COMANCHE	Washita	
		Fredericksburg	

Figure 1. Stratigraphic chart of Cretaceous and Tertiary rocks in southern Louisiana, showing series, group, and formation names used in Plates 1, 2, and 3. From Johnston et al (2000).

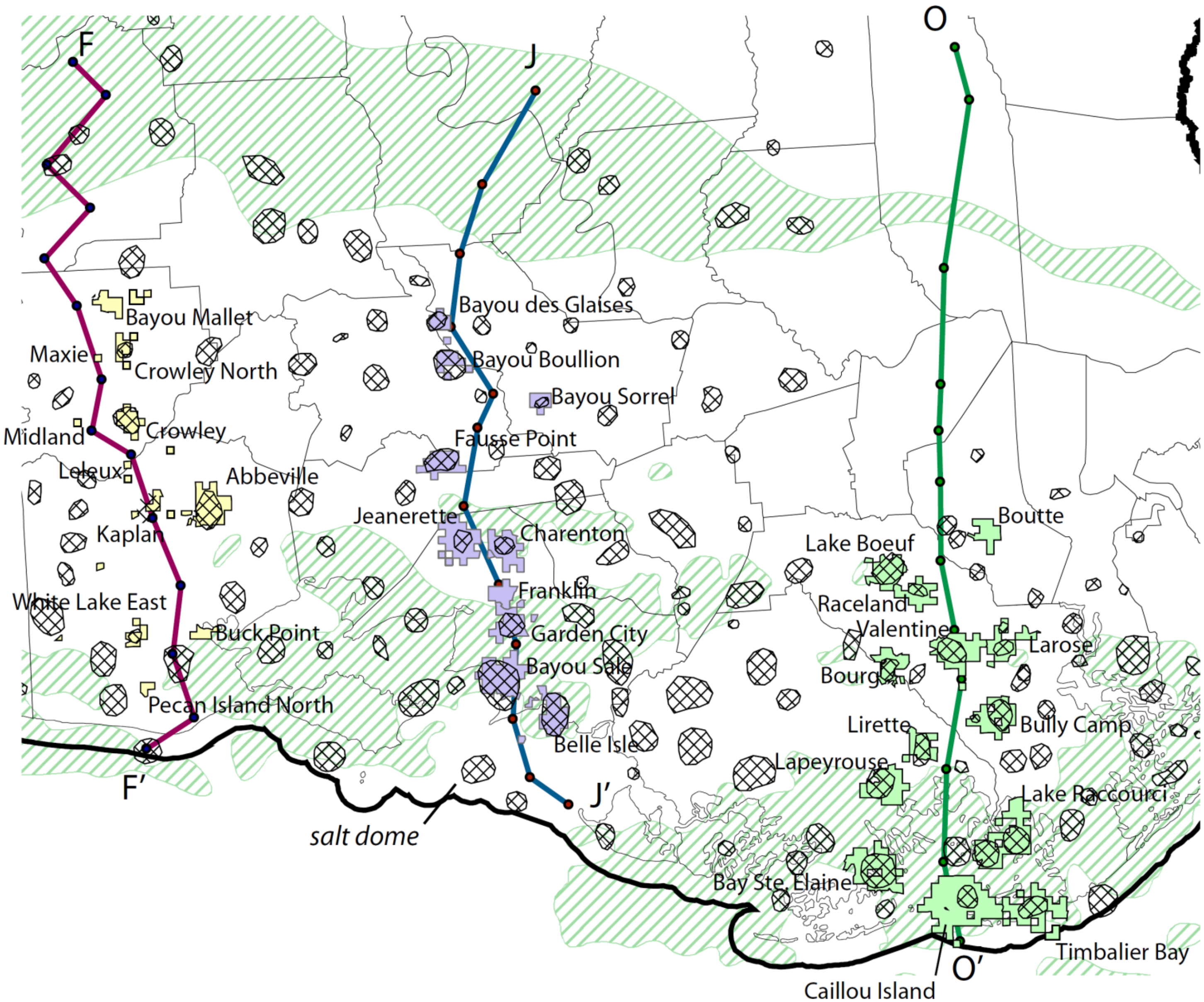

Figure 2. Map of portion of southern Louisiana showing three north-south cross-section lines from Bebout and Gutierrez (1982, 1983) and 34 oil and gas fields. Also shown are locations of salt domes and parish boundaries. See Plates 1, 2, and 3 for geologic sections and plots showing pressure and production for the 34 fields.

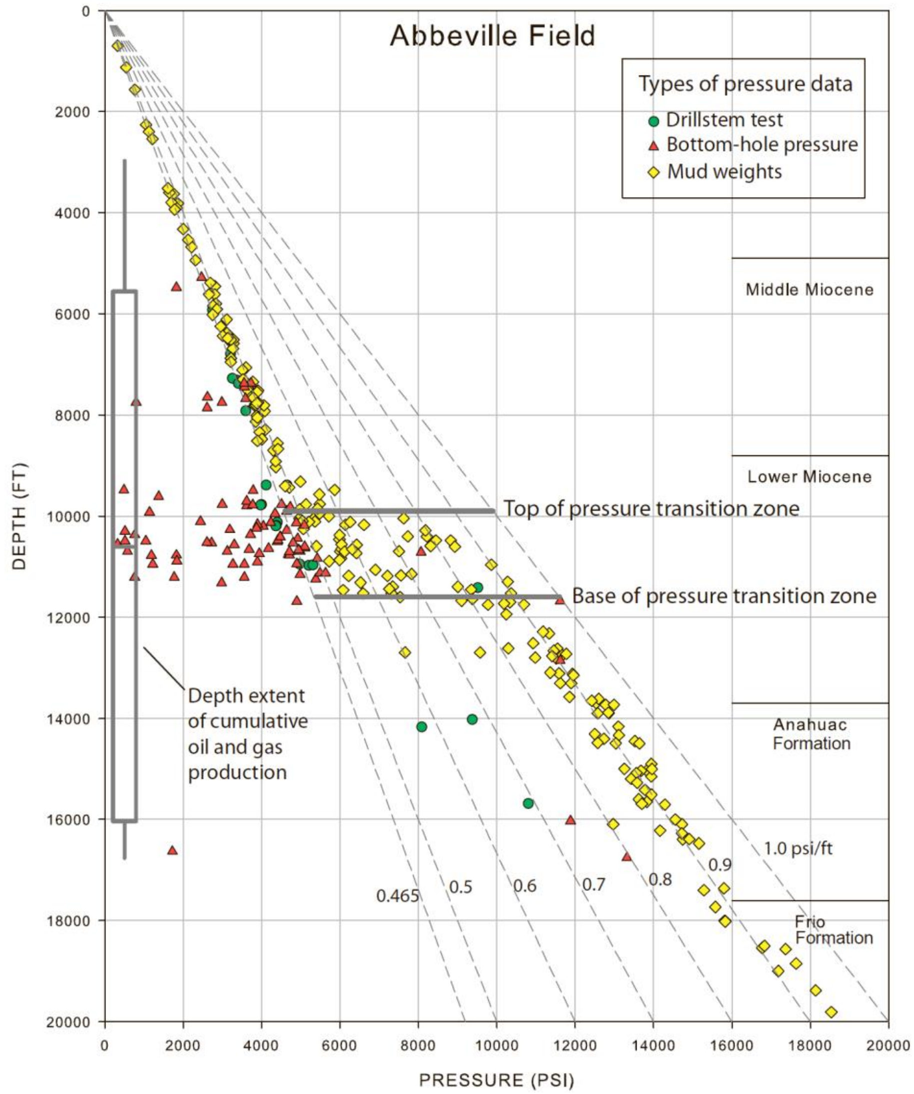

Figure 3. Pressure as a function of depth in Abbeville field, southern Louisiana (Figure 2); pressure data taken from IHS Energy Group (2006). Depths of tops of geologic formations are approximate. Pressure gradient lines range from hydrostatic (0.465 psi/ft) to lithostatic (1.0 psi/ft). Criteria for top and base of pressure transition zone are described in the text. Box-and-whiskers plot at left gives depth range for cumulative oil and gas production. Eighty percent of production is between 5530 and 16,020 ft, the depth range encompassed by the box; the median depth lies at 10,560 ft. Ten percent of production lies within the range of the upper whisker above the box and another ten percent within the range of the lower whisker.

Field order	Line	Well No.	Field name	Pressure transition zone		Depth of top, 10th, 50th, 90th percentiles, and base of production					Cumulative production		
				Top ft	Base ft	Top ft	10 ft	50 ft	90 ft	Base ft	Oil MMB	Gas BCF	Water MMB
1	FF'	1	Bayou Mallet South	9,550	10,300	2,436	4,470	8,241	9,900	9,969	14	42	120
2	FF'	2	Crowley North	9,550	11,700	2,693	6,383	11,224	11,842	13,799	35	528	318
3	FF'	3	Maxie	10,250	11,700	6,122	10,156	11,318	12,045	13,577	1	72	12
5	FF'	4	Crowley	9,300	12,100	1,733	7,685	10,736	11,779	12,697	13	241	52
6	FF'	5	Midland	9,700	11,400	6,022	9,640	11,322	11,931	12,035	9	472	70
9	FF'	6	Leleux	10,200	11,000	10,592	10,740	14,345	16,141	17,067	8	497	31
11	FF'	7	Kaplan	10,900	12,000	10,359	11,386	16,645	16,923	21,242	17	293	47
12	FF'	8	Abbeville	9,900	11,600	2,979	5,555	10,604	16,029	16,757	17	254	70
14	FF'	9	White Lake East	11,600	12,100	4,953				11,800	35	69	171
13	FF'	10	Buck Point	14,350	15,300	12,473	13,762	13,983	14,595	15,223	5	165	8
22	FF'	11	Pecan Island North	12,500	13,200	12,618	12,618	13,756	14,100	14,357	3	125	3
4	JJ'	1	Bayou Des Glaises	11,200	13,600	6,953	8,820	9,651	11,434	12,845	9	42	12
7	JJ'	2	Bayou Bouillon	10,000	13,000	2,931	9,976	10,840	12,616	13,801	31	147	38
8	JJ'	3	Bayou Sorrel	11,250	11,750	6,971	8,720	9,464	11,039	13,226	42	191	521
10	JJ'	4	Fausse Pointe	8,750	12,300	815	7,457	9,288	12,656	14,219	38	190	103
15	JJ'	5	Jeanerette	10,500	14,200	2,160	11,070	12,538	13,707	16,209	27	567	197
16	JJ'	6	Charenton	10,650	13,200	944				14,210	44	40	567
18	JJ'	7	Franklin	13,300	14,700	7,316	11,076	11,837	13,030	13,587	14	82	70
19	JJ'	8	Garden City	14,400	15,500	12,714	14,820	15,499	16,981	19,420	25	904	140
23	JJ'	9	Bayou Sale	11,300	15,200	6,219	9,750	12,130	13,695	18,490	142	2,236	270
24	JJ'	10	Belle Isle	10,100	15,200	7,863	11,756	13,026	16,821	17,576	33	1,112	79
17	OO'	1	Boutte	11,137	11,450	9,692	10,324	11,022	12,179	12,449	8	181	31
20	OO'	2	Lake Boeuf	11,150	13,200	8,652	10,301	11,735	13,043	15,328	19	376	69
21	OO'	3	Raceland	10,500	12,000	3,771				15,075	16	101	128
25	OO'	4	Valentine	8,800	12,200	1,105	8,800	11,141	11,463	12,609	46	826	97
26	OO'	5	Larose	12,200	13,000	9,971	10,832	11,169	12,141	14,969	21	138	46
27	OO'	6	Bourg	12,000	13,200	10,341	10,621	11,335	12,602	15,244	1	371	18
28	OO'	7	Bully Camp	7,600	12,150	3,477	6,057	8,836	11,121	12,869	78	221	78
29	OO'	8	Lirette	11,400	12,000	1,429	8,263	9,893	15,914	16,952	13	1,064	71
30	OO'	9	Lapeyrouse	12,350	14,550	5,036	12,470	14,569	15,518	17,200	12	647	48
31	OO'	10	Lake Raccourci	13,000	15,000	8,974	11,409	13,823	16,116	16,598	29	1,066	24
32	OO'	11	Bay Ste. Elaine	9,000	15,700	2,699	8,566	13,798	15,427	18,036	151	932	155
33	OO'	12	Caillou Island	8,900	17,900	1,542	8,448	13,105	17,580	21,814	574	2,398	569
34	OO'	13	Timbalier Bay	12,200	18,000	1,561	7,070	9,630	13,980	19,632	291	674	455

Table 1. Oil and gas fields in southern Louisiana, listing top and base of pressure transition zone, production depths, and cumulative production. [Field order, fields as numbered in Figure 8; Line and Well No. refer to sections on Plates 1, 2, and 3; MMB, million barrels; BCF, billion cubic feet].

Map of Depth to Pressure Transition Zone

Using mud-weight data, pressure transition zones were defined in 86 fields in southern Louisiana (Figure 4), and depths to the top and base of the pressure transition zone (Figures 5 and 6) were mapped using a geostatistical package. In general, the pressure transition zone is shallower in the northwest, north, and southeast portions of the map and deepens in the coastal areas. However, the maps shown in Figures 5 and 6 differ in detail because the thickness of the pressure transition zone varies across the area. For example, the thick pressure transition zone in Caillou Island and Bay Ste. Elaine fields along the coast (Figure 4) results in a deep base (Figure 6) and a shallow top (Figure 5). Another area with a deep base and a shallow top results from the thick transition zones in Jefferson Island, Avery Island, and Weeks Island fields.

The depth to base of the pressure transition zone (Figure 6) is consistent with an earlier map of the top of geopressure based on individual wells (Figure 7). The map in Figure 7 shows the areas in which the 0.5 psi/ft pressure gradient is encountered at a depth greater than 13,000 ft. The two east-west-trending areas adjacent to the Louisiana coast in Figure 7 lie within areas in which the base of the pressure transition zone is encountered at a depth greater than 13,100 ft (Figure 6). However, along the coast, the top of the pressure transition zone (Figure 5) rises to depths shallower than shown for the single surface in Figure 7.

Depth Extent of Oil and Gas Production Intervals

The depth range of oil and gas production in each field is defined by a box-and-whiskers plot (Figure 3, Plates 1, 2, and 3). To represent both gas and oil production in a single box-and-whiskers plot, gas is expressed in barrels of oil equivalent (6000 cubic feet of gas at standard temperature and pressure equals one barrel of oil). The whiskers, which are the lines extending above and below the box, show the vertical extents of the shallowest and deepest 10 percent of oil and gas production; the remaining 80 percent of production lies within the box (see example in Figure 3). Within each box, a single horizontal line defines the median depth of production. Some production records combine oil and gas production over very large vertical intervals (10,000 ft or more), so that the true production depths cannot be determined. Consequently, production data from intervals greater than 2000 ft were not included in determining the box-and-whiskers plots. For three fields — White Lake East, Charenton, and Raceland — a box could not be determined due to inadequate data; so only the total depth range (the whiskers) is shown.

Production and Pressure Transition along Three Lines

Pressure transition zones are shown for 11 oil and gas fields projected to line F-F' in Plate 1; of these, Crowley North field is the largest, with cumulative production of 528 billion cubic feet of gas (BCFG) and 35 million barrels of oil (MMBO) (IHS Energy Group, 2006). Bebout et al. (1992) characterized 10 of the 11 fields as faulted anticlines (White Lake East field was not included in their tabulation). The pressure transition zone outlined in the pressure-depth plots and by vertical bars on the cross-section F-F' lies within the depth range 9300 to 12,000 ft from Bayou Mallet field to Abbeville field (Plate 1). As a consequence, the pressure transition zone lies within progressively younger strata basinward (southward). South of Abbeville field, in Buck Point and Pecan Island North fields, the pressure transition zone lies deeper, with the base of the zone at 15,300 ft in Buck Point field. The deepening of the transition zone in this area is substantiated through comparisons with three other data sets: (1) the Buck Point and Pecan Island North fields lie within or close to the mapped areas (Plate 1) where the top of 0.5 psi/ft lies deeper than 13,000 ft, (2) the match between the base of the transition zone and the top of geopressure from Bebout and Gutierrez (1983; black arrows in the cross section on Plate 1), and (3) the presence of sandstones on the SP log to a depth greater than 16,000 ft in well 12 in the cross-section on Plate 1.

Bayou Sale field is the largest field on line J-J' that is shown on Plate 2, with cumulative production exceeding 2000 BCFG. From north to south, the pressure transition zone lies in the Oligocene Frio Formation (Bayou des Glaises field), in the younger Oligocene Anahuac Formation (Bayou Boullion and Bayou Sorrel fields), in the lower Miocene strata (Fausse Pointe through Garden City fields) and in middle Miocene strata (Bayou Sale and Belle Isle fields). In three fields (Bayou des Glaises, Bayou Sorrel, and Franklin), the box denoting 80 percent of oil and gas production is shallower than the top of the pressure transition zone. In six fields, the median and most of the production box overlap the pressure transition zone. In the Belle Isle field, which is characterized as a salt dome and is the second largest field on line J-J', a thick pressure transition zone extends from 10,000 to 15,000 ft and productive reservoirs extend from 8,000 to 17, 500 ft.

On line O-O' in Plate 3, the pressure transition zones in 13 fields all lie in Miocene strata, with the same southward-younging progression as on lines F-F' and J-J'. Three large fields, each with known resources in excess of 290 MMBO and 500 BCFG in Upper Miocene strata (Bay Ste. Elaine, Caillou Island, and Timbalier Bay), are located near the coastline and have pressure transition zones and production zones of large vertical extent. In six other fields (Boutte, Lake Boeuf, Valentine, Bully Camp, Lapeyrouse, and Lake Raccourci), the median and most of the production box overlap the pressure transition zone. In two fields (Larose and Bourg), the box denoting 80 percent of oil and gas production is mostly or entirely shallower than the top of the pressure transition zone. In Lirette field, the production box covers a much larger interval than the pressure transition zone because large quantities of gas have been produced from zones as deep as 17,000 ft, some 5000 ft below the base of the pressure transition zone.

Geological Controls on Pressure Zones and Producing Intervals

The relations among pressure transition zones, production intervals, and regional geology are portrayed in Figure 8, in which the 34 fields plotted on lines F-F' (Plate 1), J-J' (Plate 2), and O-O' (Plate 3) and listed in Table 1 are interspersed and represented on a single dip section. The fields with the deepest pressure transition zones (fields 13, 18, 19, 30, 31, 34, Table 1) have been discussed in preceding paragraphs, as have the two fields with producing intervals that lie thousands of feet below their respective pressure transition zones (fields 8, 11). The top of the pressure transition zone for the 34 fields lies between 7600 and 14,400 ft and the base lies between 10,300 and 18,000 ft. There is little apparent relation between the depth of the pressure transition zone and individual formations. The general north-south trend of increasing depth of the pressure transition zone is interrupted by four fields (25, 28, 32, 33), of which the southernmost two have extensive pressure transition zones. With only two exceptions (fields 8, 18), the pressure transition zones overlap all or part of the box portions of the production zones, which represent 80 percent of production. The top of overpressure is located where thick shale sequences are overlain by sandstone-dominated strata, as has been documented previously (for example, Dickinson, 1953; Powley, 1984; Leftwich, 1993).

Gas production increases from north to south (Figure 9), from less than 100 BCFG in the north to more than 1000 BCFG in the south. Oil production varies greatly, with no discernible north-south trend, except for the high cumulative oil production in the three southernmost fields (32-34). Water production tends to track oil production.

The four largest fields in terms of total hydrocarbon production (Figure 9) — Bayou Sale (23), Bay St. Elaine (32), Caillou Island (33), and Timbalier Bay (34) — are characterized by production intervals and pressure transition zones that span large vertical ranges (Figure 8). The large ranges presumably reflect the greater geologic complexity and larger numbers of reservoirs in these fields.

The strong relation between the top of overpressure and the location of oil and gas reservoirs is further demonstrated by plotting the median production depth against the depth of the base of the pressure transition zone (Figure 10). The median depth of production is shallower than the base of the pressure transition zone in all but 3 of 31 fields (Figure 10). A previous study by Fertl and Leach (1990), which was based upon thousands of wells drilled in 139 oil and gas fields in southern Louisiana, tabulated the vertical separation between the depth of the field and the depth at which mud weights were increased (Figure 11). Their graphs show that the bulk of oil and gas deposits are located within ±2000 ft of the depths where mud weights reach 10.5 to 14.0 ppg (0.55 to 0.73 psi/ft), and are generally located shallower than the depths where mud weights reach 18.0 ppg (0.94 psi/ft). The results shown in Plates 1, 2, and 3 and Figures 8 and 10, which are based on field-wide compilations, appear consistent with these earlier findings, which were based on individual wells.

Figure 4. Location of fields used to map the top and base of the pressure transition zone in Figures 5 and 6. Eleven fields used in discussion of deep production are underlined.

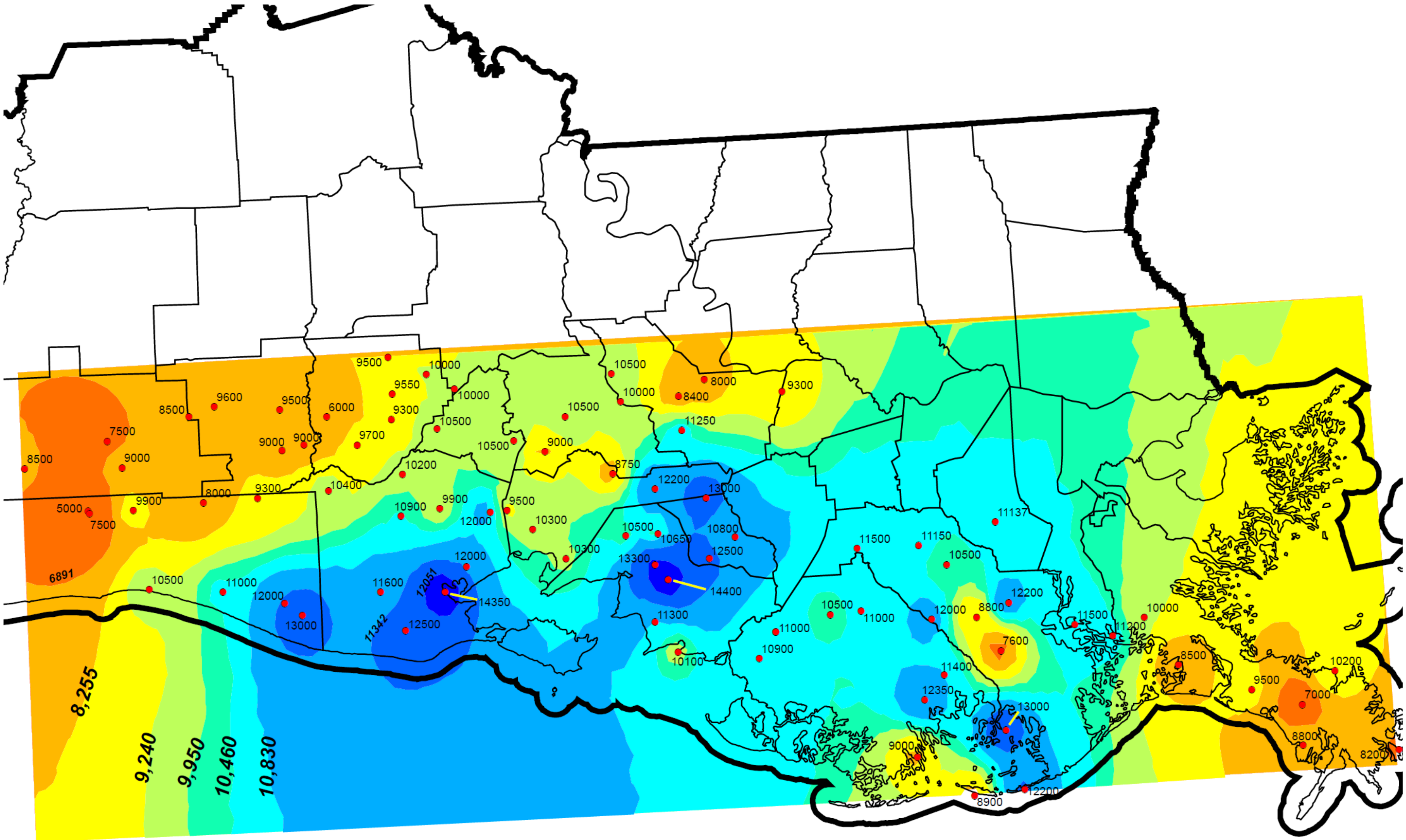

Figure 5. Map of top of pressure transition zone in 86 fields. Depth in feet, with shallower depths shown in brighter colors (red) and deeper depths in darker colors (blue).

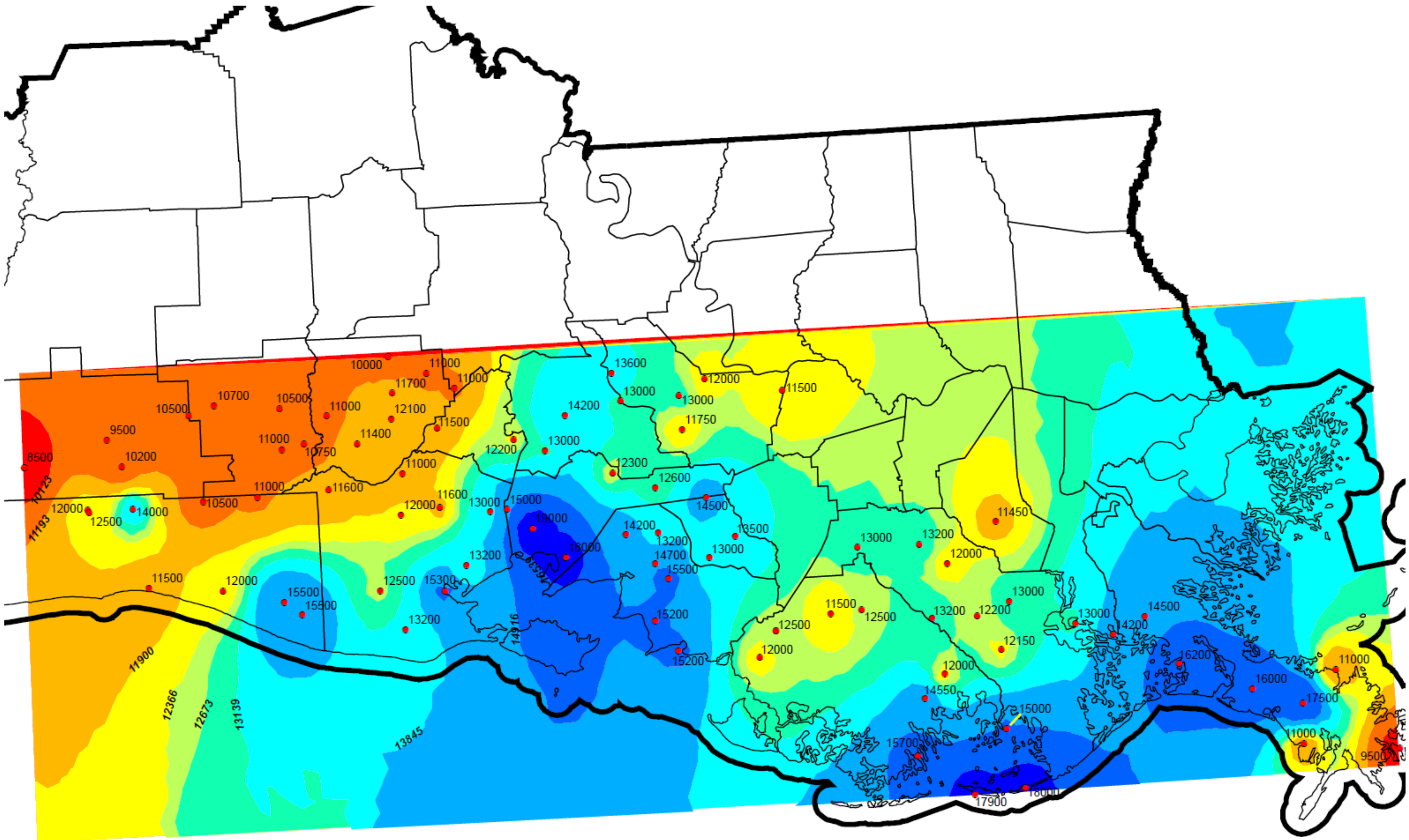

Figure 6. Map of base of pressure transition zone in 86 fields. Depth in feet, with shallower depths shown in brighter colors (red) and deeper depths in darker colors (blue).

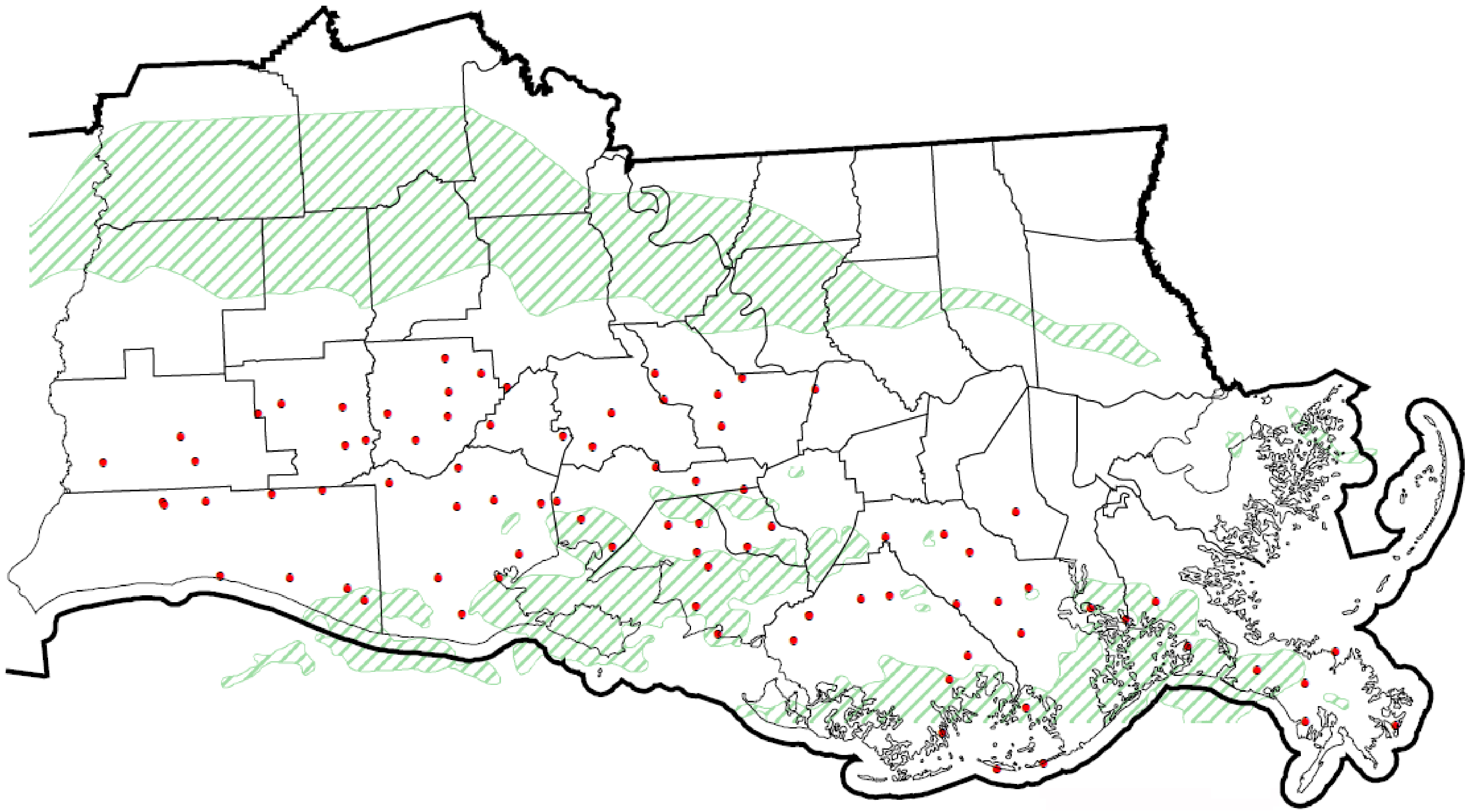

Figure 7. Map of areas (green shading) where the pressure-depth ratio of 0.5 psi/ft lies deeper than 13,000 ft (Wallace et al, 1981). Red dots show field locations of present study; field names given in Figure 4.

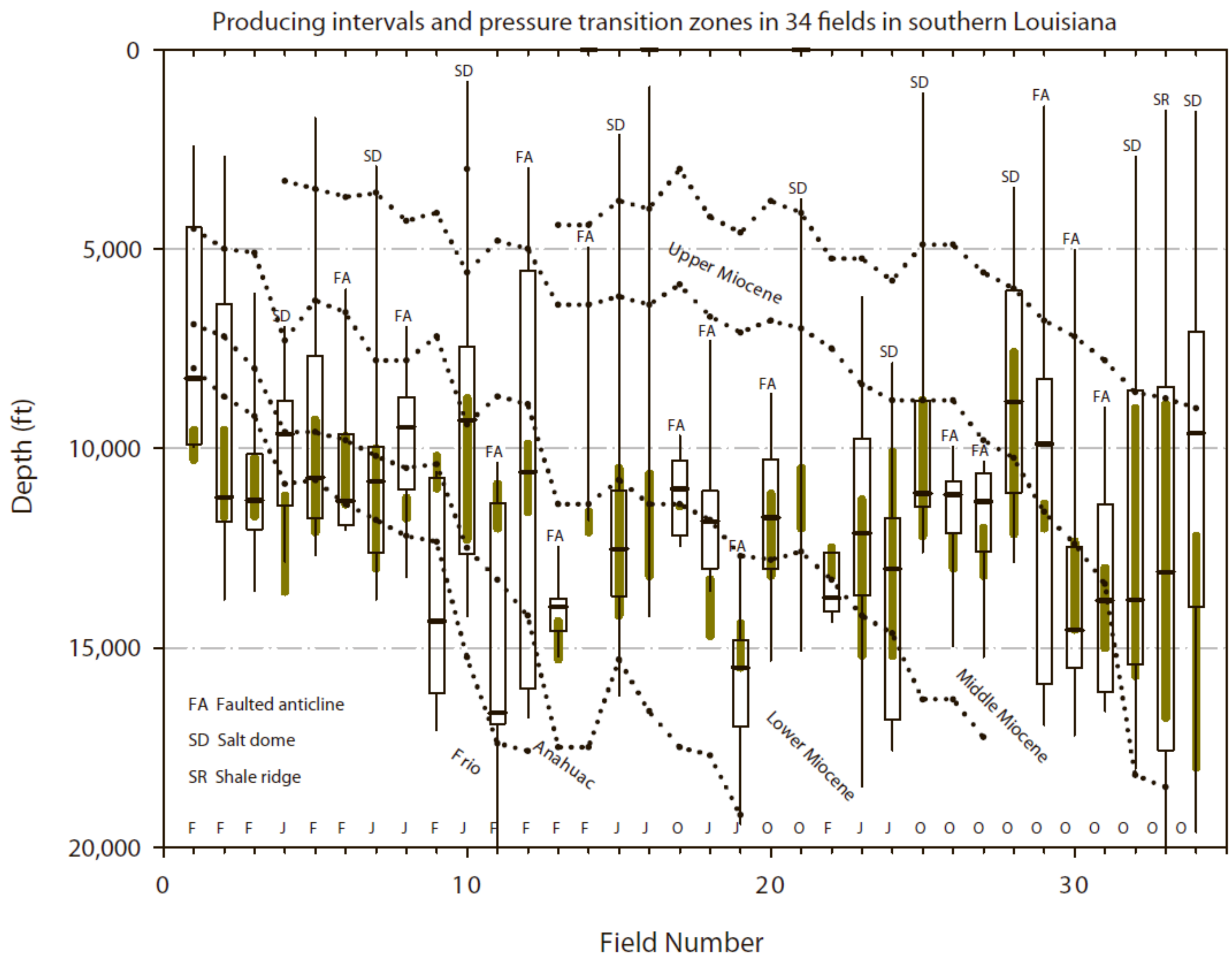

Figure 8. Pressure transition zones (solid yellow bars) and box-and-whiskers production plots for 34 fields in southern Louisiana. Box represents 80 percent of oil and gas production; short horizontal bar within box is median depth of production; upper and lower whiskers represent shallowest and deepest 10 percent of production, respectively. Letters F, J, and O refer to lines F-F', J-J', and O-O' shown in Plates 1, 2, and 3, respectively. See Table 1 for line of origin and name of each field; fields are interlaced to a common dip section, and arranged from north to south, with Bayou Mallet South field to the left and Timbalier Bay field to the right. Formation tops are approximate, obtained by projecting to lines of sections in Plates 1, 2, and 3. Field designations (faulted anticline, salt dome, shale ridge) taken from McCampbell et al. (1964), Harrison et al. (1970), and Anderson et al. (1989).

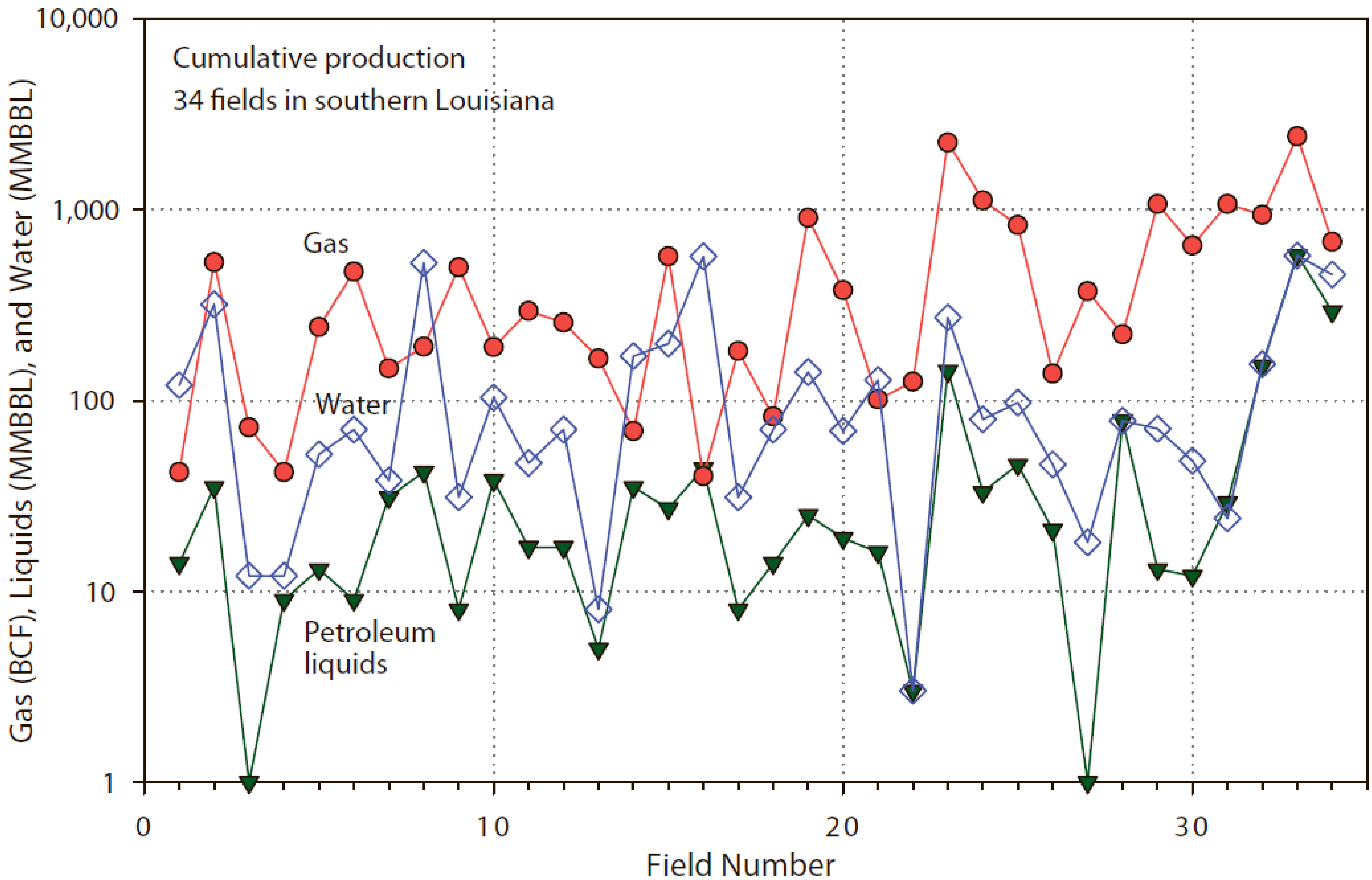

Figure 9. Cumulative oil, water, and gas production by field (IHS Energy Group, 2006) along the same interlaced profile as shown in Figure 8. [BCF, billion cubic feet; MMBBL, millions of barrels].

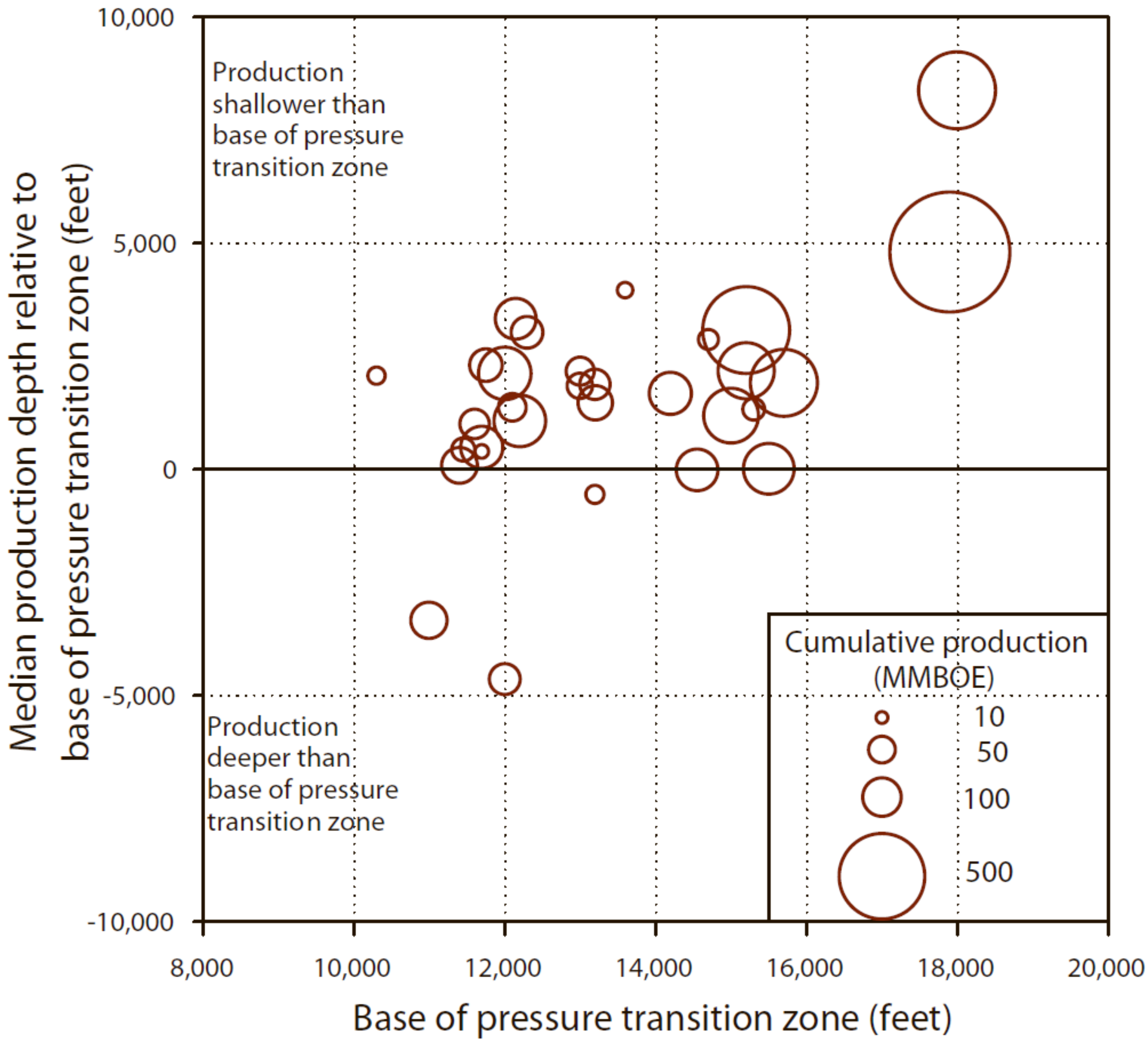

Figure 10. Vertical separation between pressure transition and production intervals in 31 fields, as represented by the base of the pressure transition zone and the depth of median production. Areas of circles are proportional to cumulative production, in million barrels of oil equivalent (MMBOE); four examples are shown in the key.

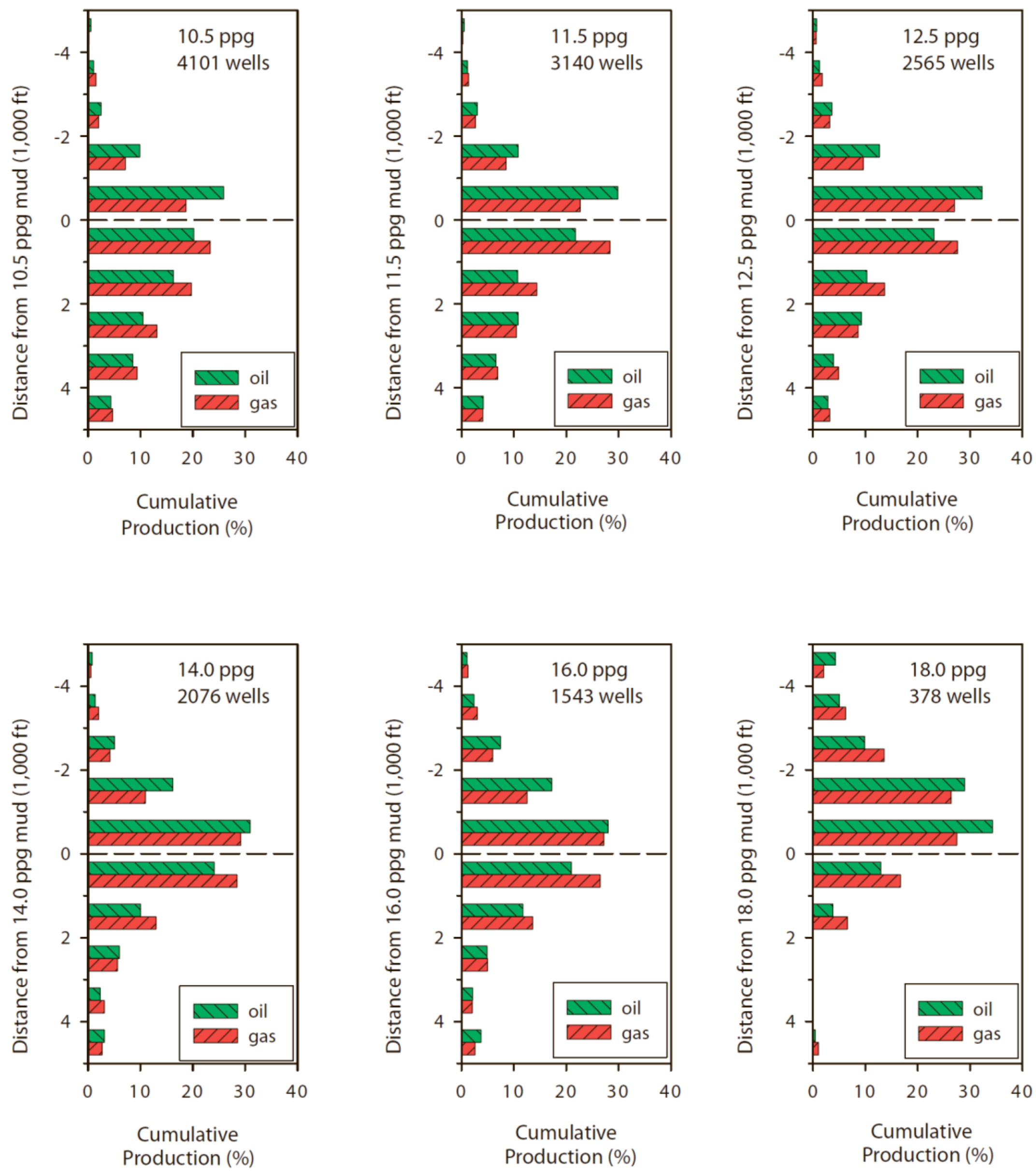

Figure 11. Distribution of hydrocarbon production with respect to distance above and below the depth of an increase in mud weight in pounds per gallon (ppg). Six levels of mud-weight increase are shown, with number of wells varying with mud weight. Data are for 139 south Louisiana Tertiary fields from Fertl and Leach (1990).

Excess Pore Pressure and Effective Stress

The difference between actual pore pressure P_a and hydrostatic pore pressure P_h is defined here as the excess pore pressure, P_x

$$P_x = P_a - P_h. \qquad (1)$$

The actual pressure P_a is approximated by the mud weight pressure P_m, computed according to equation 1, so that

$$P_x \sim P_\mathrm{m} - P_h \qquad (2)$$

where the hydrostatic pore pressure P_h is computed as 0.465 psi/ft times the depth in feet, z.

The total vertical lithostatic stress σ_L is taken as the depth in feet times 1.0 psi/ft. The difference between σ_L and P_a is the effective stress σ_e. As P_a is approximated by P_m, then

$$\sigma_\mathrm{e} \sim \sigma_L - P_\mathrm{m} \qquad (3)$$

Consequently, the total lithostatic load σ_L is the sum of the hydrostatic pore pressure P_h, the excess pore pressure P_x and the effective stress σ_e,

$$\sigma_L = P_h + P_x + \sigma_\mathrm{e} \sim P_\mathrm{m} + \sigma_\mathrm{e} \qquad (4)$$

Mud-weight pressure increases linearly with depth, with a slope that parallels or slightly exceeds the lithostatic gradient below the base of the pressure transition zone in many fields (Leleux, Kaplan, and Abbeville fields, Plate 1; Garden City and Bayou Sale fields, Plate 2; Lirette and Lapeyrouse fields, Plate 3). In the Kaplan field (Figure 12), the equivalent pressure gradient is about 0.85 psi/ft (16.3 ppg) at the base of the pressure transition zone at 12,000 ft, slightly greater than 0.9 psi/ft (17.3 ppg) from 13,000 to 16,000 ft, and 0.93 psi/ft (18 ppg) from 16,000 to 20,000 ft. Excess pore pressure P_x and effective stress σ_e are computed according to equations 2 and 3 for the Kaplan well (Figure 12). Excess pore pressure is zero above 8000 ft, begins to increase at 8500 ft, and increases sharply within the transition zone. At 13,000 ft, the excess pore pressure is 6000 psi, which is equivalent to the hydrostatic pressure. From 13,000 to 20,000 ft excess pore pressure increases at a rate just slightly greater than the hydrostatic pressure gradient of 0.465 psi/ft. Effective stress, on the other hand, increases normally with depth above the transition zone, drops sharply within the transition zone, and is nearly constant at 1200 psi from 13,000 to 20,000 ft.

Excess pore pressure and effective stress were computed for each mud-weight pressure below the pressure transition zone in Kaplan and six other fields (Figure 13). Because mud weight is generally maintained constant after setting casing, the mud weights were edited to remove constant values between casing points. For example, if 17.5 ppg was recorded at 16,000, 16,240, and 16,650 ft, then only the entry at 16,000 ft was retained. Also, multiple mud weight entries at the same depth were deleted. For example, if mud weights of 15.3, 16.0, and 17.0 ppg were recorded at 16,400 ft, then all three entries were deleted. This editing step also greatly reduced the number of values in wells with numerous mud weight values, reducing the bias of over-reported wells. Pressure gradients were determined by least-squares regression to the mud-weight pressure values, commencing around 1000 ft below the base of the pressure transition zone and extending as deep as data permit. Despite the editing steps, the local pressure gradients reported in Table 2 and Figure 13 were closely similar to slopes determined on unedited data. Pressure gradients in psi/ft are posted next to each segment. The pressure gradients (grad) are not independent: from equation 4, the effective stress gradient, grad(σ_e) = grad(σ_L) - grad(P_m) = 1.0 psi/ft - grad(P_m), and from equation 2, the excess pressure gradient, grad(P_x) = grad(P_m) - grad(P_h) = grad(P_m) - 0.465 psi/ft. Thus, the accuracy in the estimate of the effective stress and excess pressure gradients depends upon the error in assuming standard values for lithostatic and hydrostatic pressure gradients of 1.0 and 0.465 psi/ft, respectively.

From an inspection of the edited mud-weight pressures shown in Figure 13, the following relations can be observed at depths below the base of the pressure transition zone:

- Comparing the mud-weight pressures with the lines of constant pressure-depth ratio, it can be seen that the high mud-weight pressures produce pressure-depth ratios between 0.8 and 1.0 psi/ft. The pressure-depth ratios generally increase with depth.
- The local pressure gradient, determined by least-squares fit to the mud-weight pressures, ranges from 0.91 to 1.26 psi/ft. The local pressure gradient is lowest in the Oligocene Frio and Anahuac formations and highest in the lower and middle Miocene strata.
- The excess fluid pressure (mud-weight pressure minus hydrostatic pressure) is itself comparable to normal hydrostatic pressure and increases with depth with gradients ranging from 0.44 to 0.80 psi/ft.
- Effective stress is less than 2000 psi and can either decrease or increase with depth below the base of the pressure transition zone. The gradient of effective stress is positive or nearly zero in the Frio and Anahuac formations in the three northwestern fields, becomes negative in the lower Miocene rocks in the Garden City and Bayou Sale fields, and attains the greatest negative values in the middle Miocene rocks in the Lirette and Lapeyrouse fields.

Thus, with increasing depth, pore pressure approaches lithostatic pressure and effective stress approaches zero in the younger overpressured Miocene strata lying close to the coast. The potential for failure by faulting is greater in the younger Miocene strata than in the older Anahuac and Frio strata.

Revil and Cathles (2001) computed excess fluid pressure in shales from density logs in wells penetrating Pliocene strata in offshore Louisiana. The excess fluid pressure gradient is constant or nearly so in more than 30 of the 40 wells shown in their figures. To explain the persistence of non-zero gradients of excess fluid pressure, Revil and Cathles (2001) suggested that such overpressured zones must consist either of numerous pressure compartments with a "honeycomb of seals" or else the strata must be impermeable throughout the overpressured zone. The field-wide pressure gradients in Figure 13 present the same dilemma — high excess pressure gradients must either drive fluids upward and eventually dissipate, or else the flow system is locked by a honeycomb of seals or a continuous stack of impermeable strata.

Production below the Top of Hard Overpressure

Ninety-one fields in southern Louisiana were reviewed with respect to "deep" oil and gas production, where ―deep" is defined as more than 2000 ft deeper than the base of the pressure transition zone, which in turn is defined as the depth where pressure-depth ratios from mud weights are greater than 0.6 psi/ft. Adding the 2000-ft buffer generally assures that a reservoir is in the zone of high overpressure, where pressure-depth ratios based upon mud weights are about 0.9 psi/ft.

From an examination of the depth distribution of mud weights, roughly 55 of the 91 fields were observed to have been explored to depths greater than 2000 ft below the base of the pressure transition zone, but the other 36 fields may not have been explored much below the pressure transition zone. Eleven fields had significant production in this pressure regime (Table 3, Figure 4); in these, total production from all perforated intervals ranges from 43 to 500 BCFG, and production intervals include the Oligocene Anahuac and Frio formations and lower and middle Miocene strata. Thus, significant gas accumulations have been discovered and developed below the base of the pressure transition zone, although the median production depth generally lies above the base of the pressure transition zone, as established for 31 fields (Figure 10).

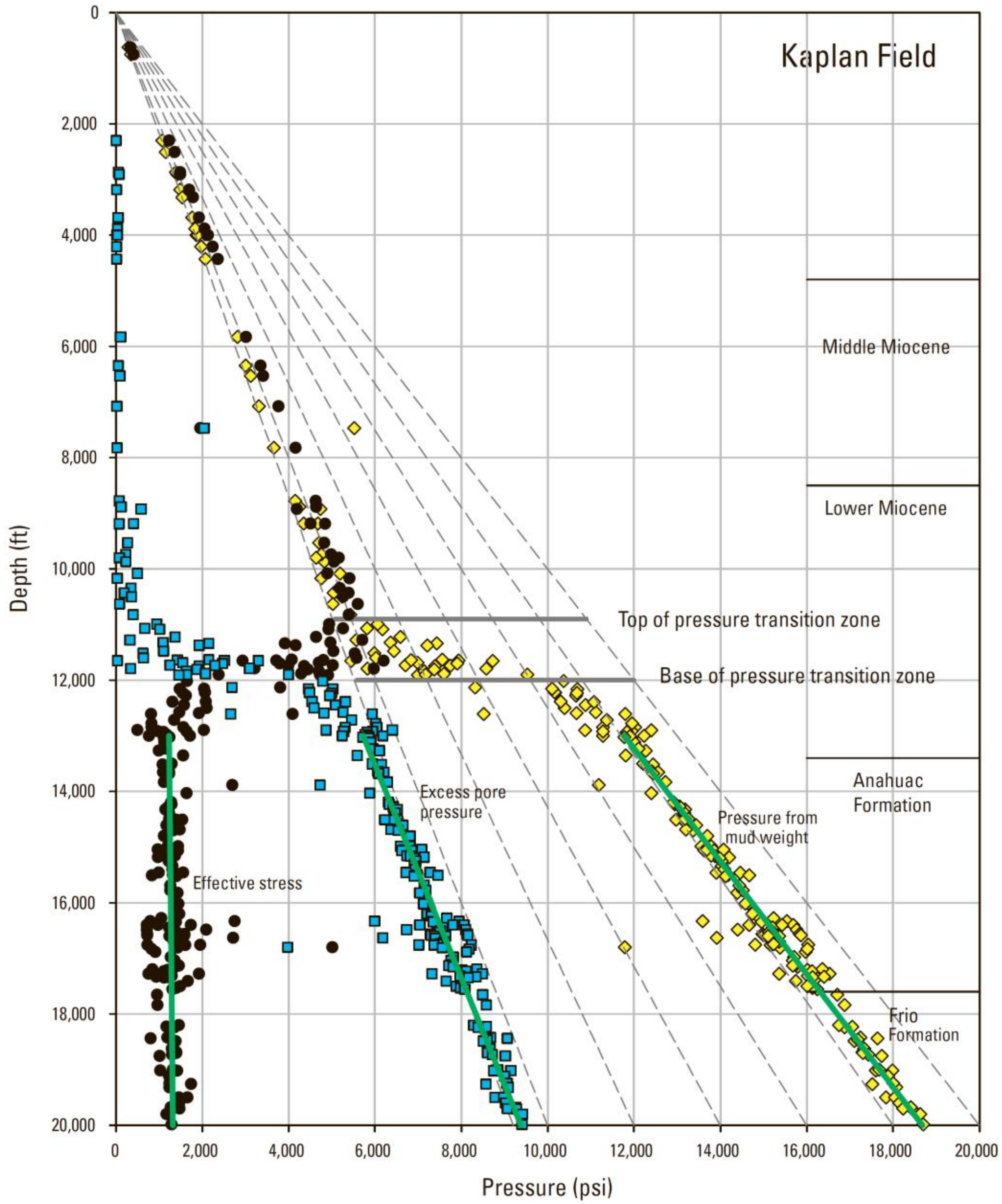

Figure 12. Pressure from mud weights as a function of depth in the Kaplan field. Excess pore pressure and effective stress were computed from mud-weight pressures as described in the text. Effective stress is around 1200 psi and increasing only slightly with depth below 13,000 ft, as indicated by the near-vertical straight line that was fit by least-squares analysis.

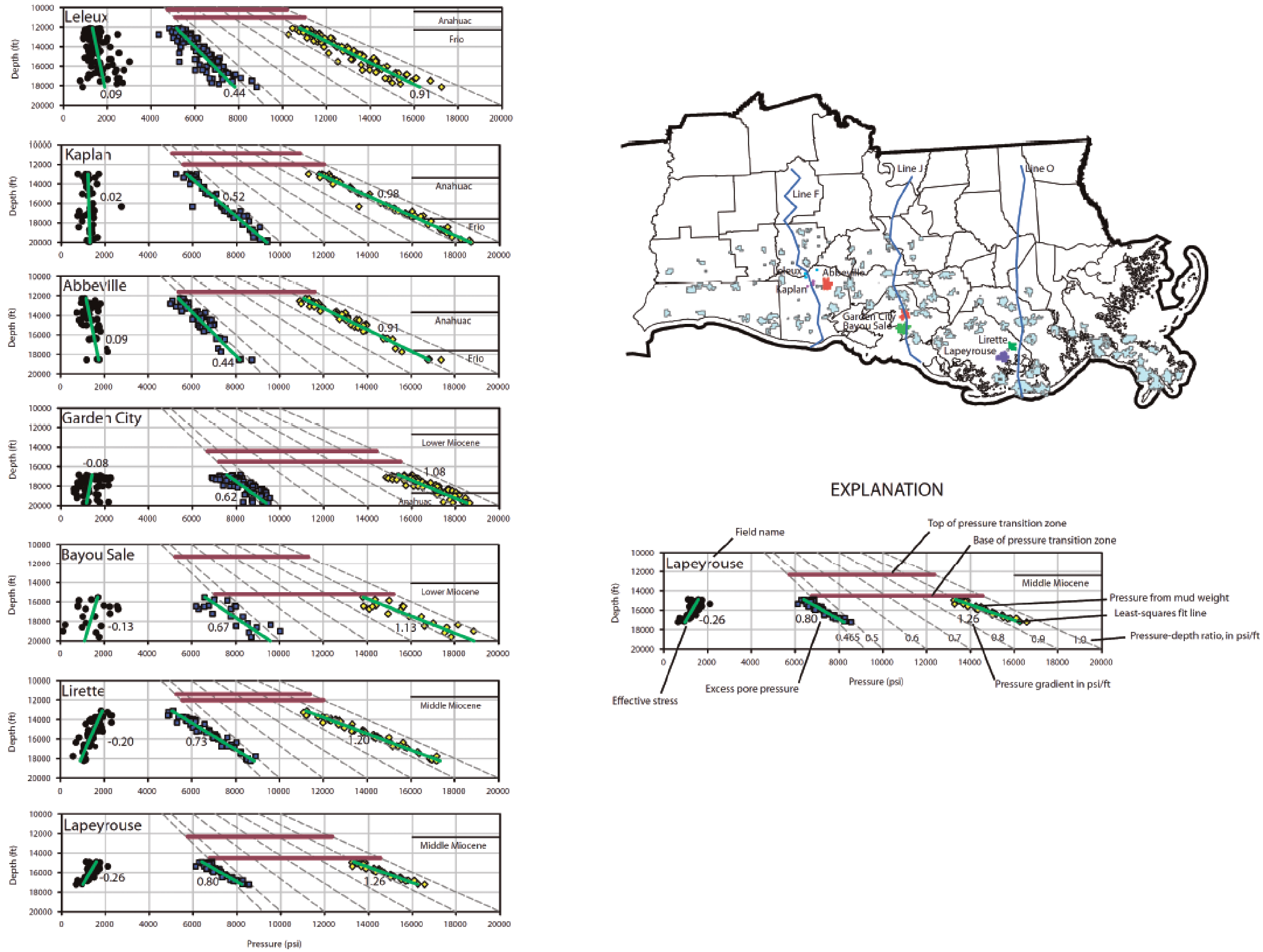

Figure 13. Line segments representing pressure from mud weights, excess pore pressure, and effective stress in seven fields. Effective stress and excess pore pressure are computed from mud weight pressure and from assumed values of hydrostatic and lithostatic pressure. Line segments represent least-squares fits to the data points, as shown in the key. The pressure gradient in psi/ft is posted next to each line segment. Dashed sloping lines represent pressure-depth ratios and horizontal solid red lines show top and base of pressure transition zone.

Field Name	Number of wells	Number of mud weight pressures	Top of interval, ft	Bottom of interval, ft	Pressure gradient, psi/ft	Excess pore pressure gradient, psi/ft	Effective stress gradient, psi/ft
Leleux	38	97	12,106	18,137	0.91	0.44	0.09
Kaplan	21	56	13,000	21,404	0.98	0.52	0.02
Abbeville	16	49	12,288	18,563	0.91	0.44	0.09
Garden City	26	62	16,820	19,710	1.08	0.62	-0.08
Bayou Sale	8	22	15,544	20,010	1.13	0.67	-0.13
Lirette	19	58	13,125	18,500	1.20	0.73	-0.20
Lapeyrouse	19	36	14,920	17,225	1.26	0.80	-0.26

Table 2. Gradients of mud-weight pressure, excess pore pressure, and effective stress below the base of the pressure transition zone in seven fields. The number of mud-weight pressures per well in each field ranges from two to three.

Field Name	No. perfed intervals	Base of pressure transition zone, feet	Shallowest top perfed interval, feet	Deepest bottom perfed interval, feet	Equivalent oil produced, MMB	Gas produced, BCF	Oil produced, MMB	Formations with deep production
Chalkley	18	10,500	12,630	15,876	88.4	502.8	4.6	Frio
Thornwell South	46	11,000	13,016	17,329	53.6	304.5	2.9	Frio
Lake Arthur	26	11,500	13,552	16,986	28.3	160.0	1.6	Frio
Leleux	28	12,000	14,076	17,300	42.8	230.8	4.4	Frio
Kaplan	27	12,000	14,352	21,314	50.8	229.9	12.5	Anahuac & Frio
Broussard	23	12,000	14,013	16,632	44.7	214.6	9.0	Frio
Garden City	9	15,500	17,557	19,434	8.5	43.4	1.3	Lower Miocene
Lake Verret West	6	13,000	16,086	16,920	12.0	61.7	1.7	Lower Miocene
Kent Bayou	9	12,500	14,508	19,154	39.4	106.4	21.7	Middle Miocene
Gibson	14	12,000	14,374	15,142	55.0	307.3	3.8	Middle Miocene
Lirette	12	12,000	14,856	16,996	20.1	108.8	1.9	Middle Miocene

Table 3. Eleven fields in southern Louisiana with production intervals deeper than 2000 ft below the base of the pressure transition zone, based upon data from wells (IHS, 2006). Field locations are shown in Figure 4. Formations in which production occurred were determined from nearby cross sections (Bebout and Gutierrez, 1982, 1983). ["Perfed" indicates that the casing was perforated for production purposes; MMB, million barrels; BCF, billions of cubic feet].

Summary and Conclusions

Pressure data derived from mud weights were the most abundant and provided the best indication of the depth distribution of overpressure conditions. Pressures derived from drillstem tests and from bottomhole pressures were much fewer in number and generally seemed to measure reduced pressure in production intervals.

The top and base of the pressure transition zone in a given field were selected based upon a pressure-depth ratio of 0.6 psi/ft; above the top of this zone this ratio is seldom exceeded, but below the base it is almost always exceeded (Plates 1, 2, and 3). Vertical extents of the pressure transition zone range from 300 ft in Boutte field to 9000 ft in Caillou Island field. Of the 34 fields included in the study, the vertical extent of the pressure transition zone is less than 1000 ft in 9 fields, between 1000 and 2000 ft in 9 fields, between 2000 and 3000 feet in 6 fields, and greater than 3000 feet in 10 fields. The cumulative production of oil and gas is greater in fields with vertical extents greater than 3000 ft than in fields with vertical extents less than 3000 ft. Vertical extents generally increase from north to south (Figure 8), reflecting an increase in geologic complexity.

Maps of the top and base of the pressure transition zone show that it lies at shallower depths in the northwest, north, and southeast portions of the map and deepens in the coastal areas. However, maps of the top and base differ in detail because the thickness of the pressure transition zone varies across the area.

Historical production in onshore Louisiana is closely tied to the depth distribution of overpressure. The depth range of 80 percent of production overlaps the pressure transition zone in all but two fields (Figure 8). Of the 30 fields in which both the pressure transition zone and the production interval could be defined, the median depth of production lies above the pressure transition zone in 9 fields, within it in 18 fields, and below it in only 3 fields (Figure 8). Stating it another way, the median production depth lies above the base of the pressure transition zone in 27 of 30 fields and within 3000 ft of it in most of these 27 fields (Figure 10). This result agrees qualitatively with the conclusions of Fertl and Leach (1990) concerning the relation between hydrocarbon production and overpressure, and although the two sets of results are not directly comparable, comparison between the 18.0 ppg case (Figure 11) and the results of Figure 10 demonstrates compatibility. The concentrations of oil and gas at or near the top of overpressure may be linked to changes in solubility of gas in water and oil in gas as functions of changes in pressure, temperature, and salinity (Gatenby, 2001).

In some fields, significant production has been obtained from reservoirs below the base of the pressure transition zone (that is, below the top of "hard overpressure"). This was the case in 11 of 55 fields having exploration drilling to depths well below the base of the pressure transition zone. This result may well understate the potential for deeper gas resources, as onshore drilling for deep targets to date may have been limited by (1) economic constraints imposed by deep drilling; (2) technical difficulties, such as the difficulty of drilling through a pressure-depleted reservoir and into a deeper overpressured sequence; and (3) regulatory constraints, such as limitations imposed by permitting regulations that restrain the exploration of potential reservoirs below producing fields.

Below the base of the pressure transition zone, mud weights indicate that pressure gradients vary in systematic manner from northwest to southeast (Figure 13 and Table 2). The pressure gradients range from 0.91 to 0.98 psi/ft in the Frio and Anahuac formations in three northwestern fields (Leleux, Kaplan, and Abbeville), and range from 1.08 to 1.26 psi/ft in the lower and middle Miocene strata in four southeastern fields (Garden City, Bayou Sale, Lirette, and Lapeyrouse). Consequently, the potential for upward fluid flow is greater in the younger (Miocene) rock sequences than in the older (Frio and Anahuac) . However, in order to retain such high internal pressure gradients, these vertically extensive overpressured sequences must be vertically impermeable, due either to the presence of numerous pressure compartments or to impermeable rocks throughout the overpressured zone. Assuming a uniform lithostatic pressure gradient across the region, the computed effective stress gradient varies in a manner complementary to the pressure gradient, being small or slightly positive in the three northwestern fields and negative in the four southeastern fields. Consequently, the potential for failure and faulting is greater in the younger (Miocene) rock sequences than in the older (Frio and Anahuac).

Acknowledgments

Patrick Trainor, an undergraduate student in petroleum engineering at the Colorado School of Mines, displayed a high level of ingenuity in organizing and plotting the large data sets required for this study. Reviews by Keith Katahara of Hydro Gulf of Mexico and Robert Morton of the USGS led to improvements in the manuscript. Comments from USGS personnel Jim Coleman, Russ Dubiel, and Janet Pitman have also been incorporated.

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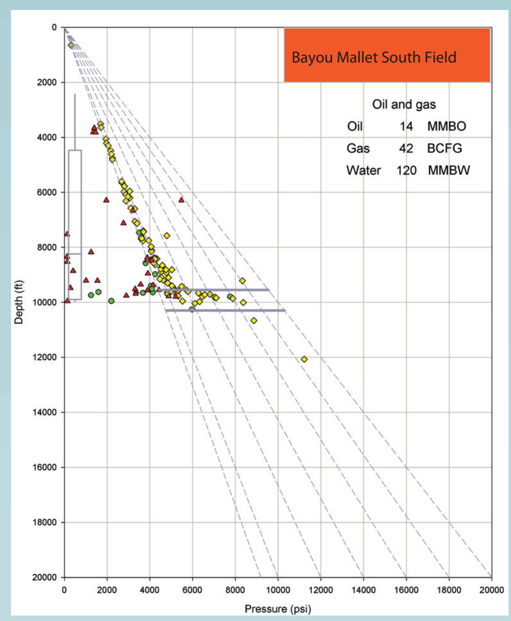
PLATE 1

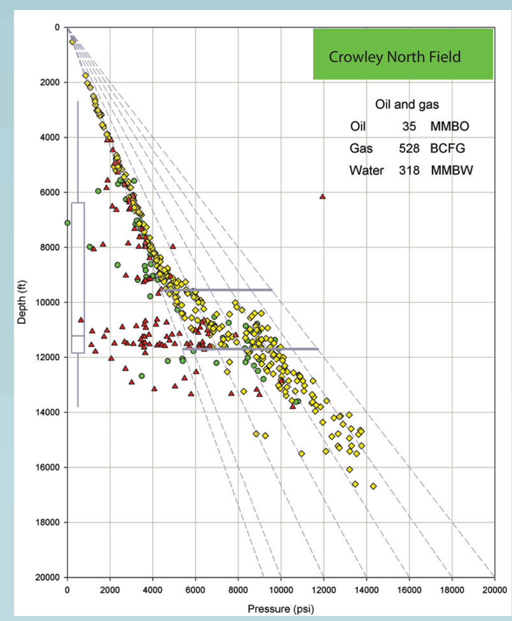
EXPLANATION

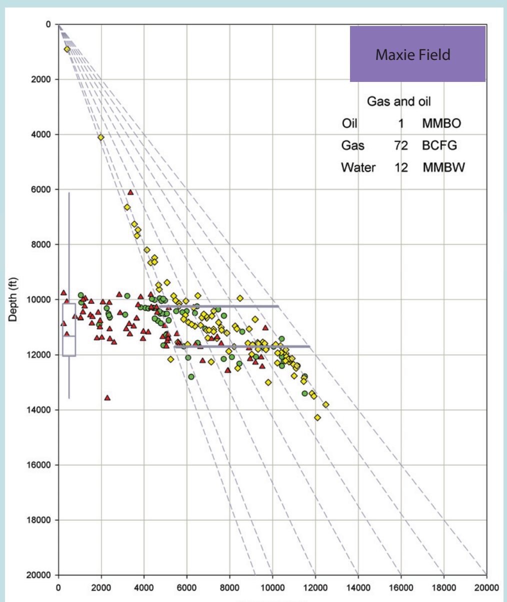
Pressure-depth plots. Pressure data from drillstem tests, mud weights, and bottom-hole pressures were extracted from a data base provided by IHS Energy Group (2006). The top and base of the pressure t ransition zones were selected by the author. Constant pressure gradients are represented by seven diagonal lines: a pressure gradient of 0.465 psi/ft represents salt water and a gradient of 1.0 psi/ft represents the lithostatic pressure gradient. Designation of a field as an oil or gas field is based on the gas-oil ratio (standard cubic feet of gas per barrel of oil): oil (<3,000), oil and gas (>3,000 and <20,000), gas and oil (>20,000 and <140,000), or gas (>140,000). Cumulative production of oil, gas, and water are from IHS Energy Group (2006). [MMBO, million barrels of oil; BCFG, billion cubic feet of gas; MMBW, million barrels of water]

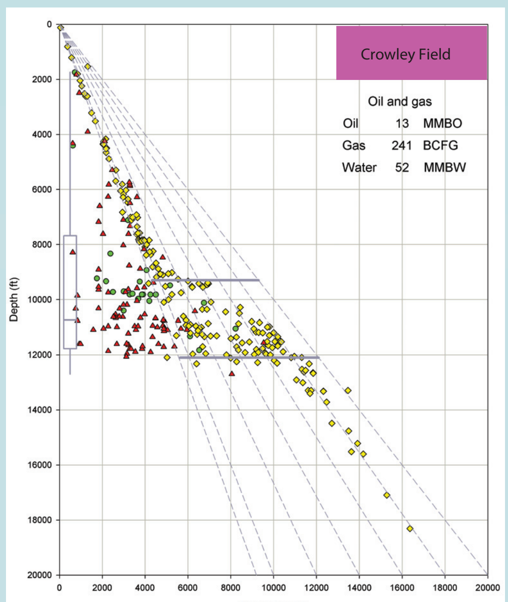
Geologic section. The geologic section is taken from Bebout and Gutierrez (1983). Vertical bars superposed on the sections represent the depth range of the pressure transition zones depicted on the pressure-depth plots.

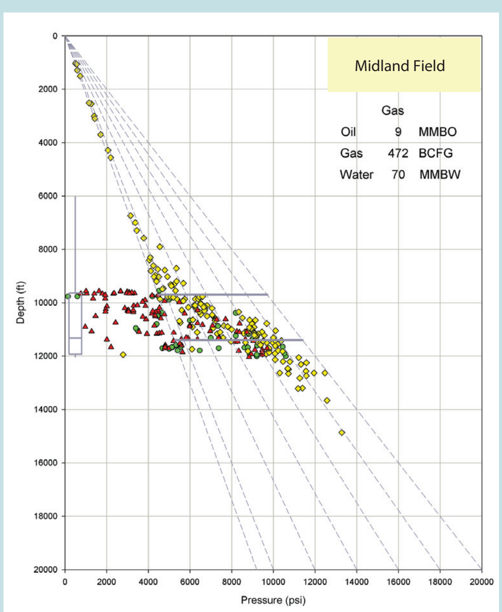
Reference map. The map shows numbered well locations for line F-F', polygons outlining oil and gas fields, location of salt domes (black hatching), parish boundaries, and the areas where the pressure-depth ratio of 0.5 psi/ft lies deeper than 13,000 ft (green diagonals, after Wallace and others, 1981).

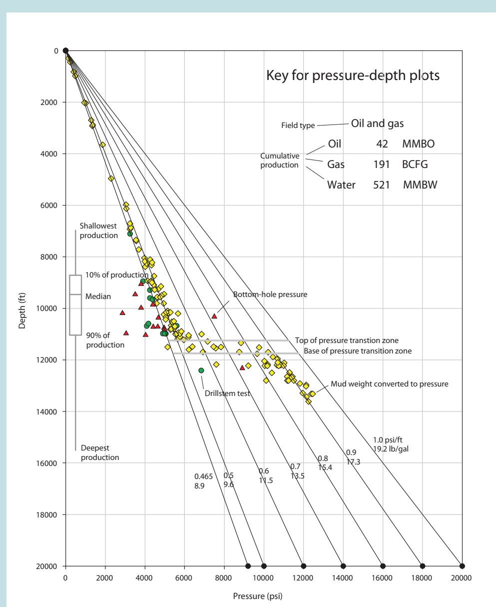


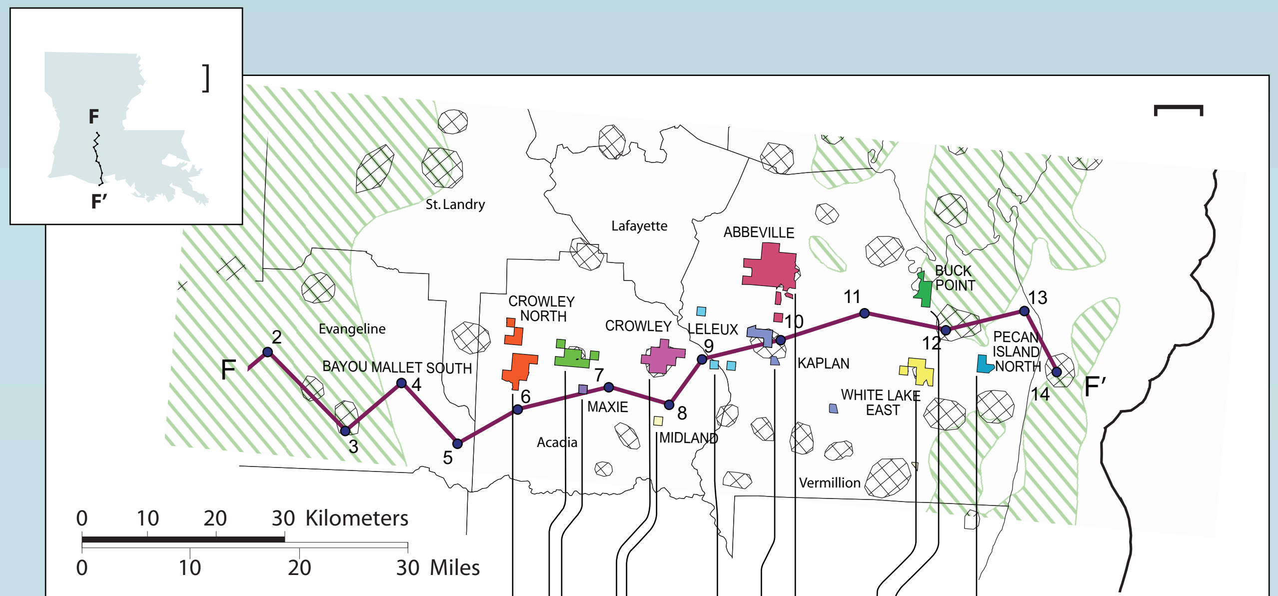


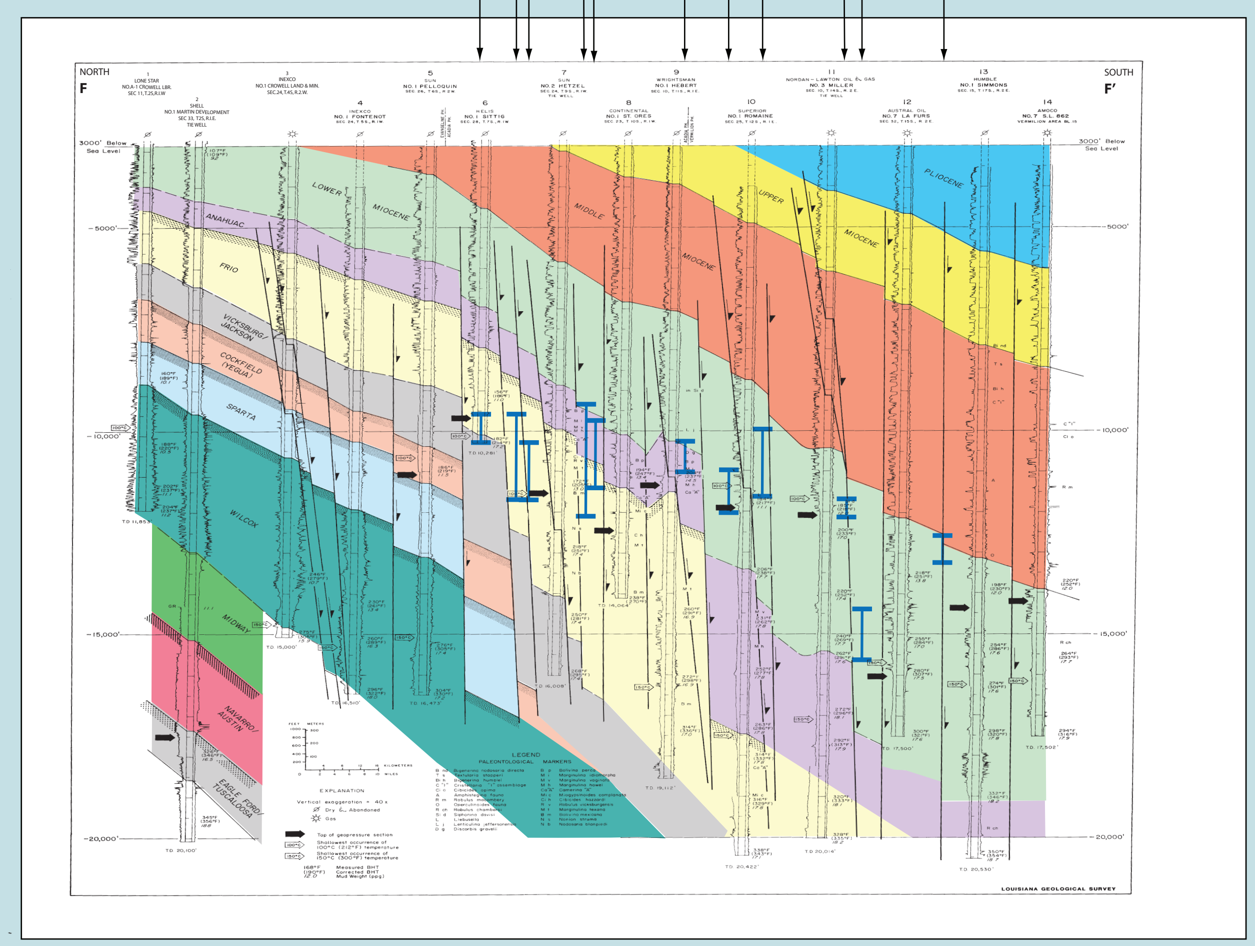


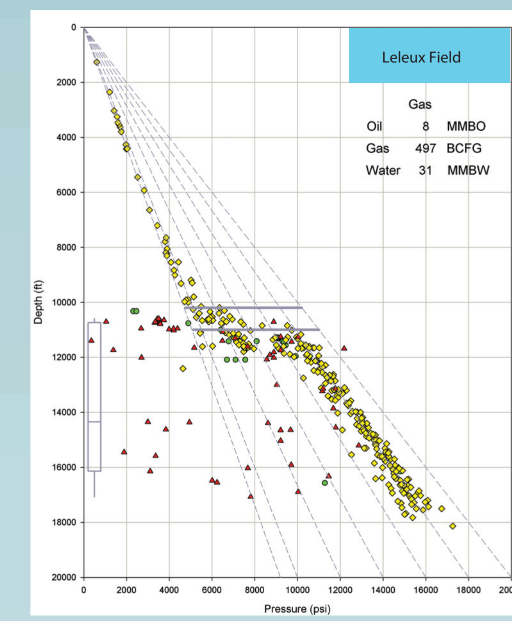


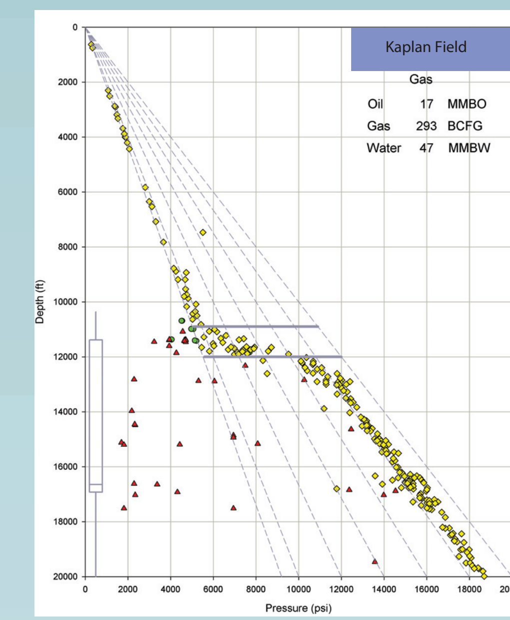


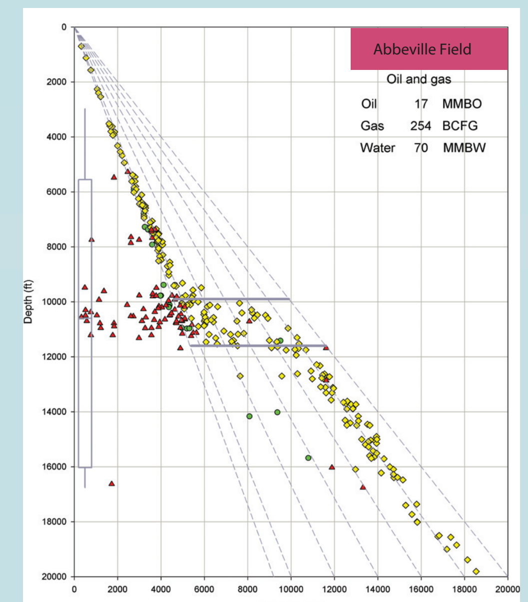


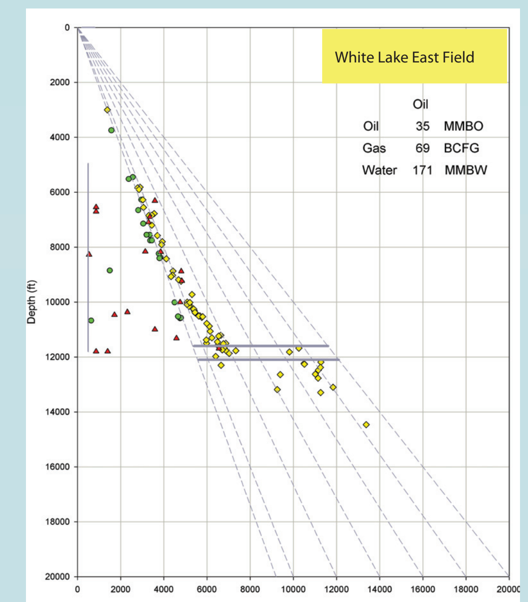


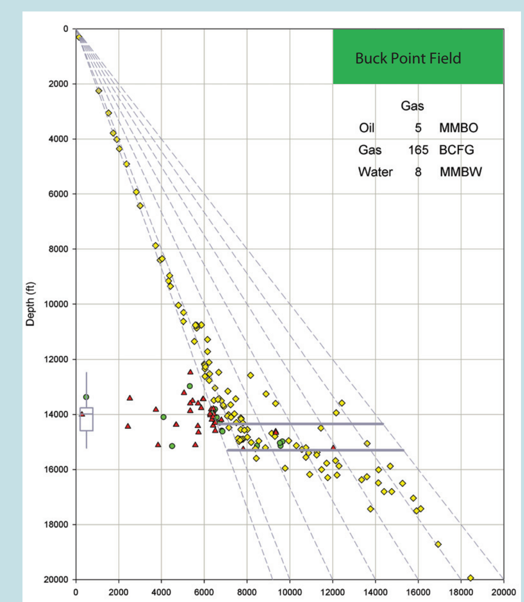


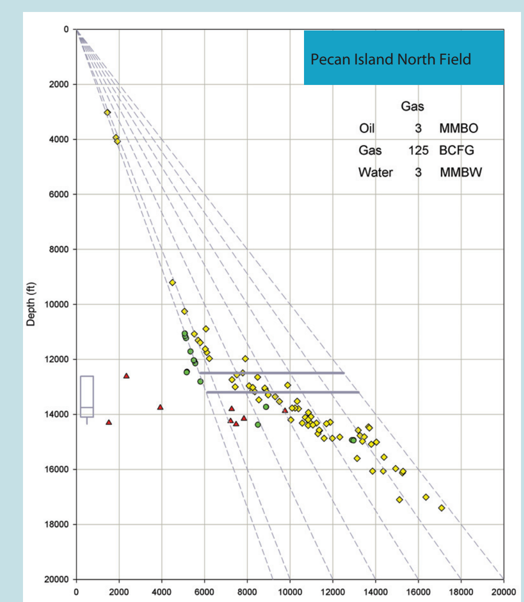












PRESSURE-DEPTH PLOTS IN OIL AND GAS FIELDS ALONG LINE F-F′, SOUTHERN LOUISIANA

By Philip H. Nelson, U.S. Geological Survey

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EXPLANATION

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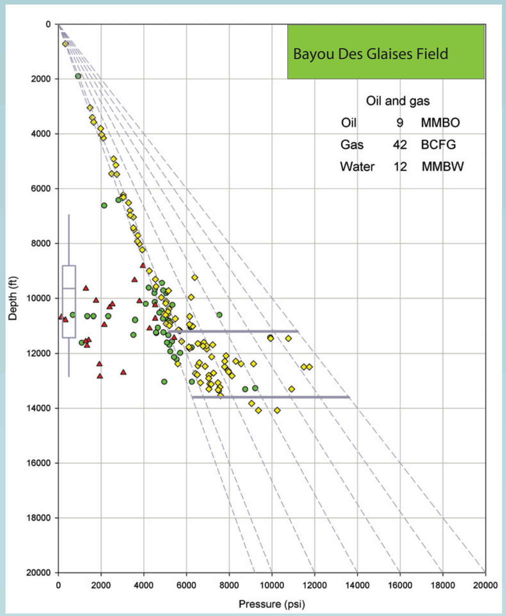
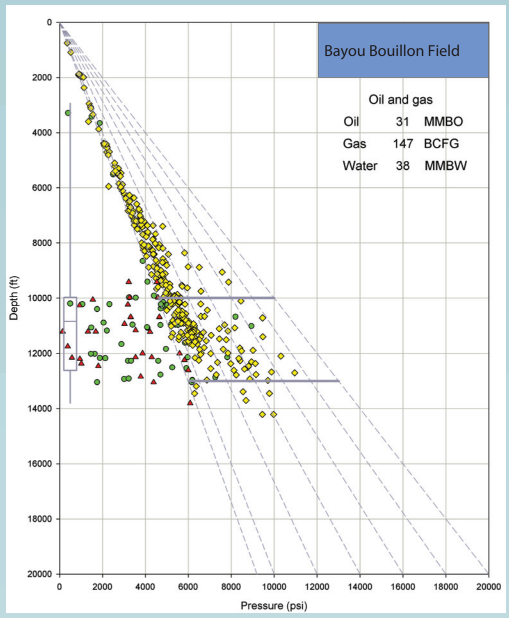
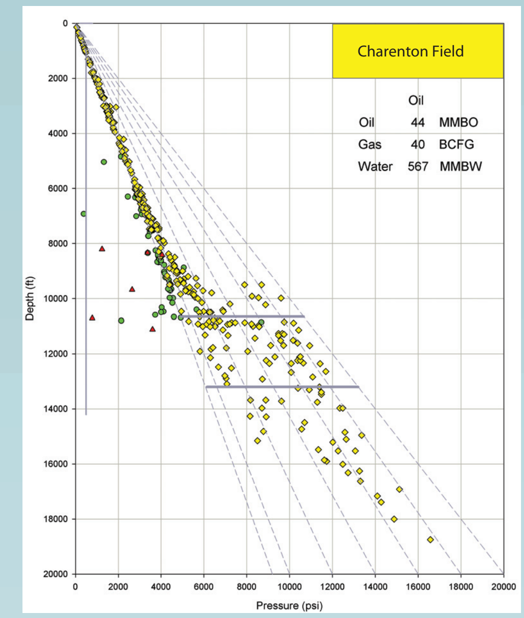
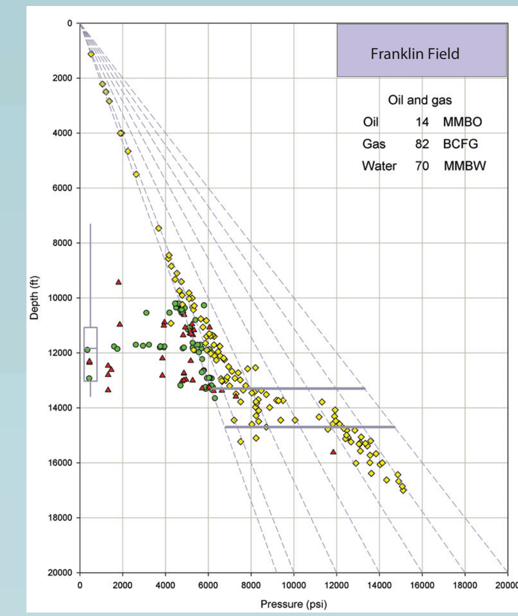
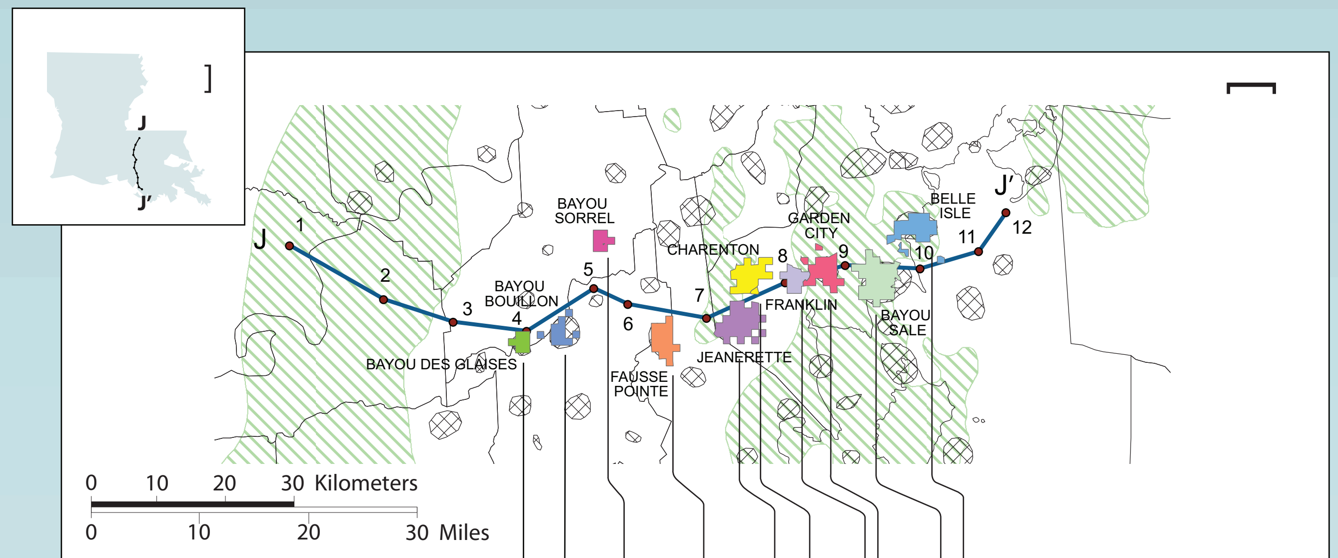
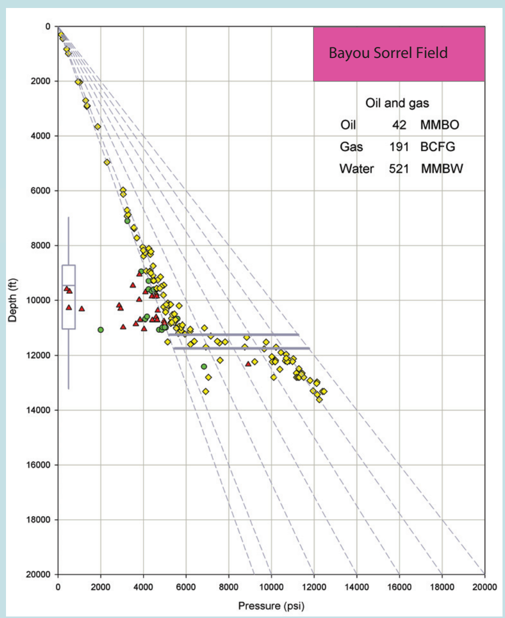


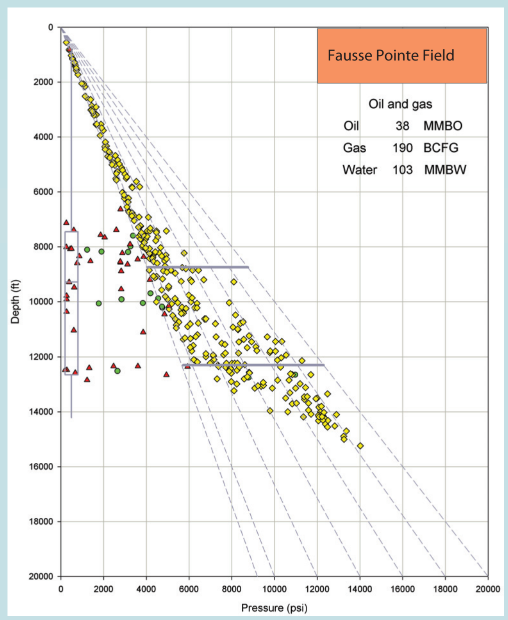


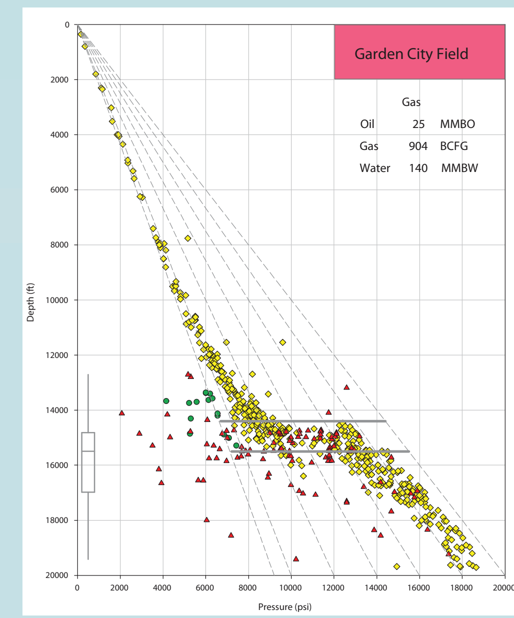


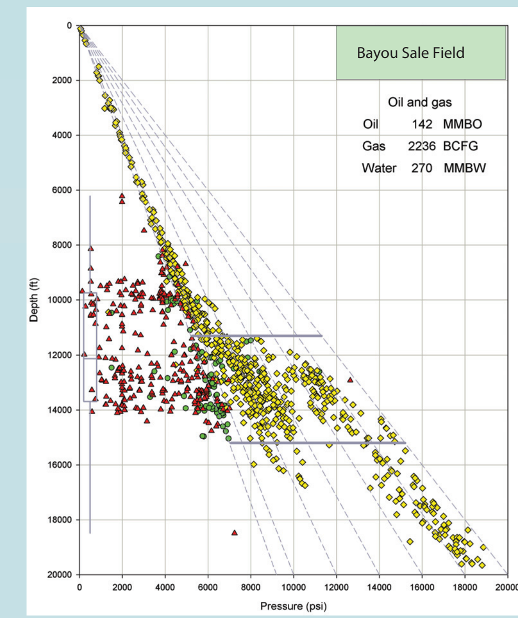


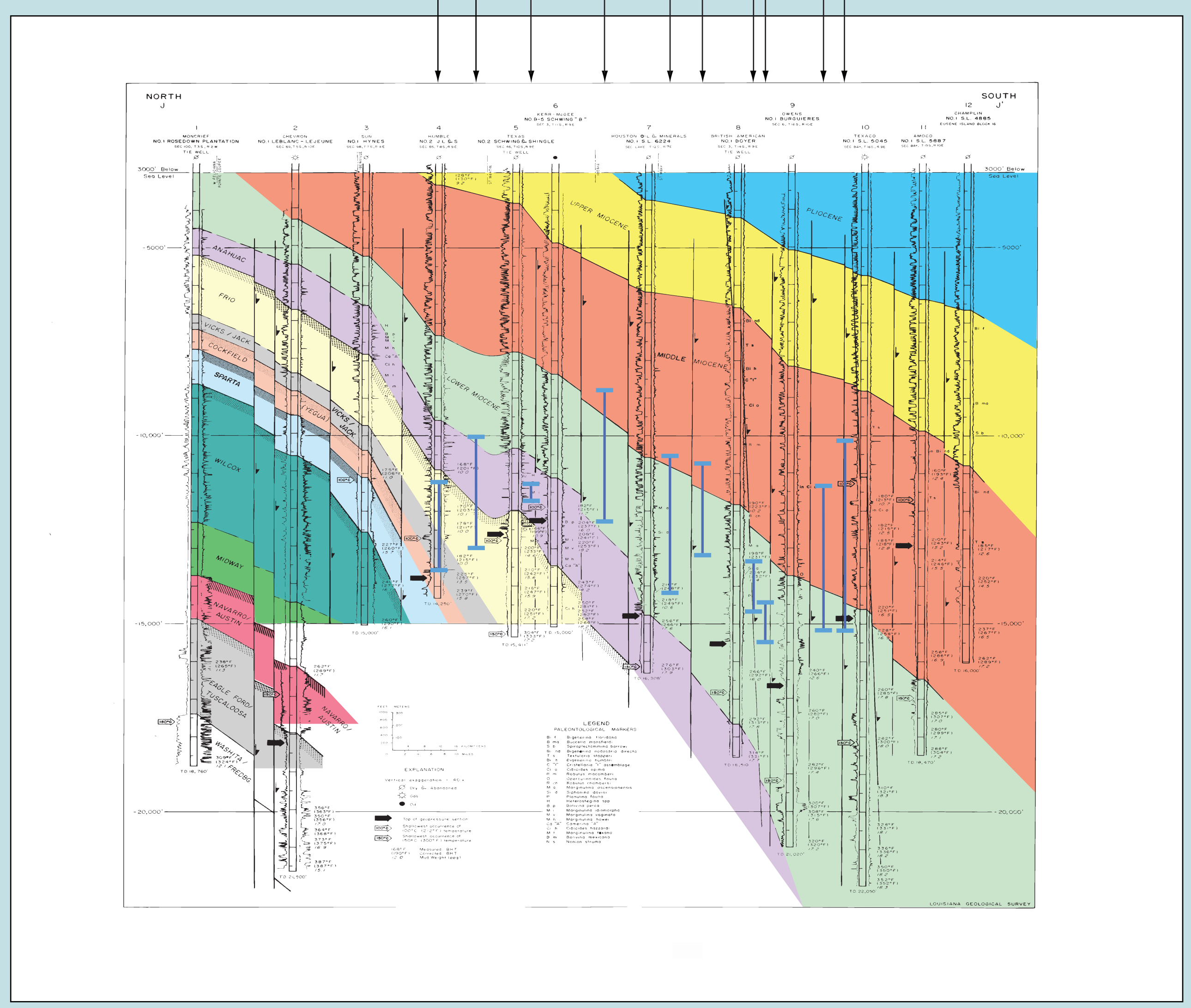


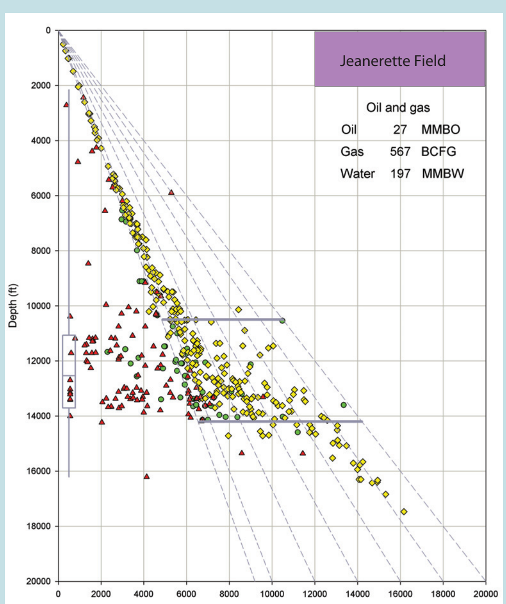


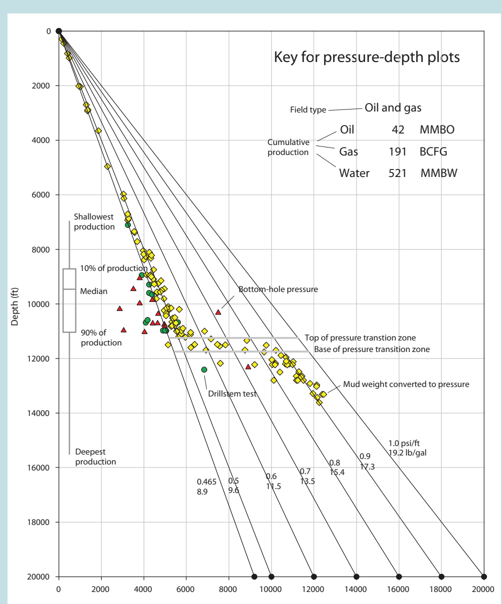


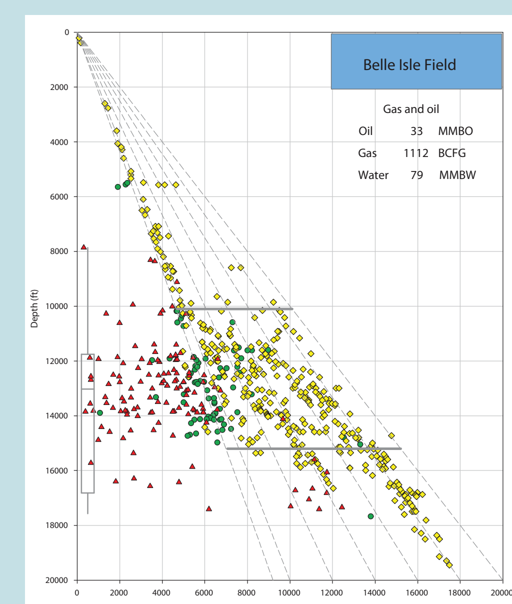












PRESSURE-DEPTH PLOTS IN OIL AND GAS FIELDS ALONG LINE J-J', SOUTHERN LOUISIANA

By Philip H. Nelson, U.S. Geological Survey

U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

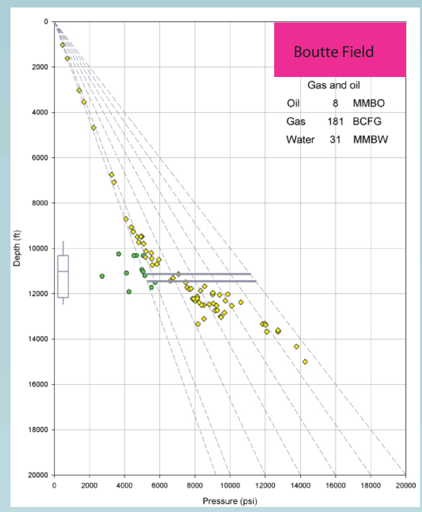
PLATE 3

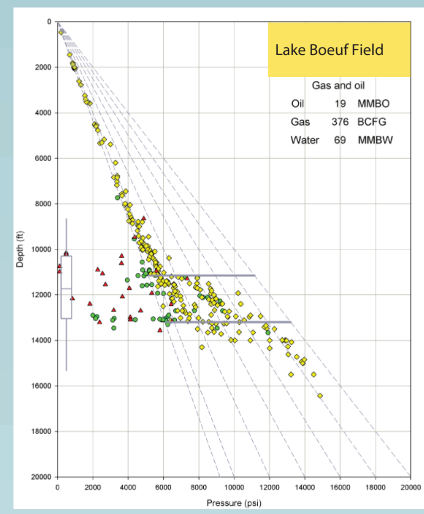
EXPLANATION

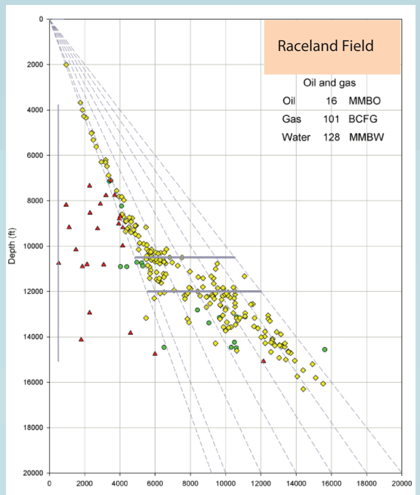
Pressure-depth plots. Pressure data from drillstem tests, mud weights, and bottom-hole pressures were extracted from a data base provided by IHS Energy Group (2006). The top and base of the pressure transition zones were selected by the author. Constant pressure gradients are represented by seven diagonal lines: a pressure gradient of 0.465 psi/ft represents salt water and a gradient of 1.0 psi/ft represents the lithostatic pressure gradient. Designation of a field as an oil or gas field is based on the gas-oil ratio (standard cubic feet of gas per barrel of oil): oil (<3,000), oil and gas (>3,000 and <20,000), gas and oil (>20,000 and <140,000), or gas (>140,000). Cumulative production of oil, gas, and water are from IHS Energy Group (2006). [MMBO, million barrels of oil; BCFG, billion cubic feet of gas; MMBW, million barrels of water]

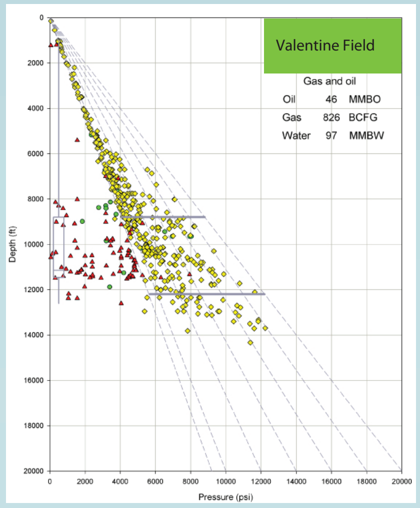
Geologic section. The geologic section is taken from Bebout and Gutierrez (1983). Vertical bars superposed on the sections represent the depth range of the pressure transition zones displayed on the pressure-depth plots.

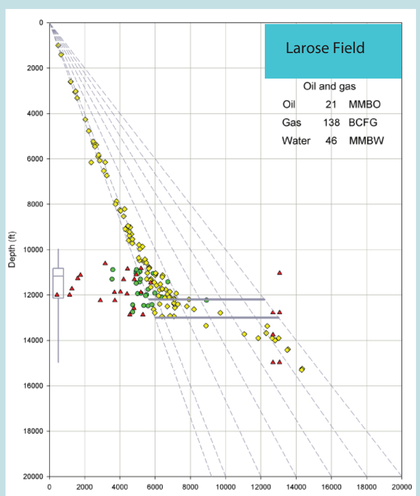
Reference map. The map shows numbered well locations for line O-O′, polygons outlining oil and gas fields, location of salt domes (black hatching), parish boundaries, and the areas where the pressure-depth ratio of 0.5 psi/ft lies deeper than 13,000 ft (green diagonals, after Wallace and others, 1981).

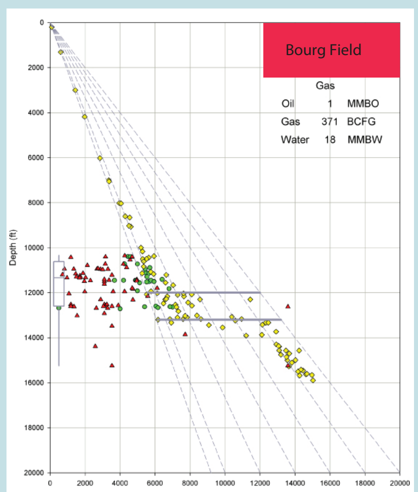


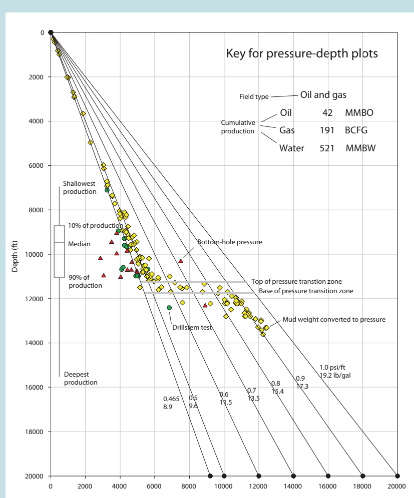


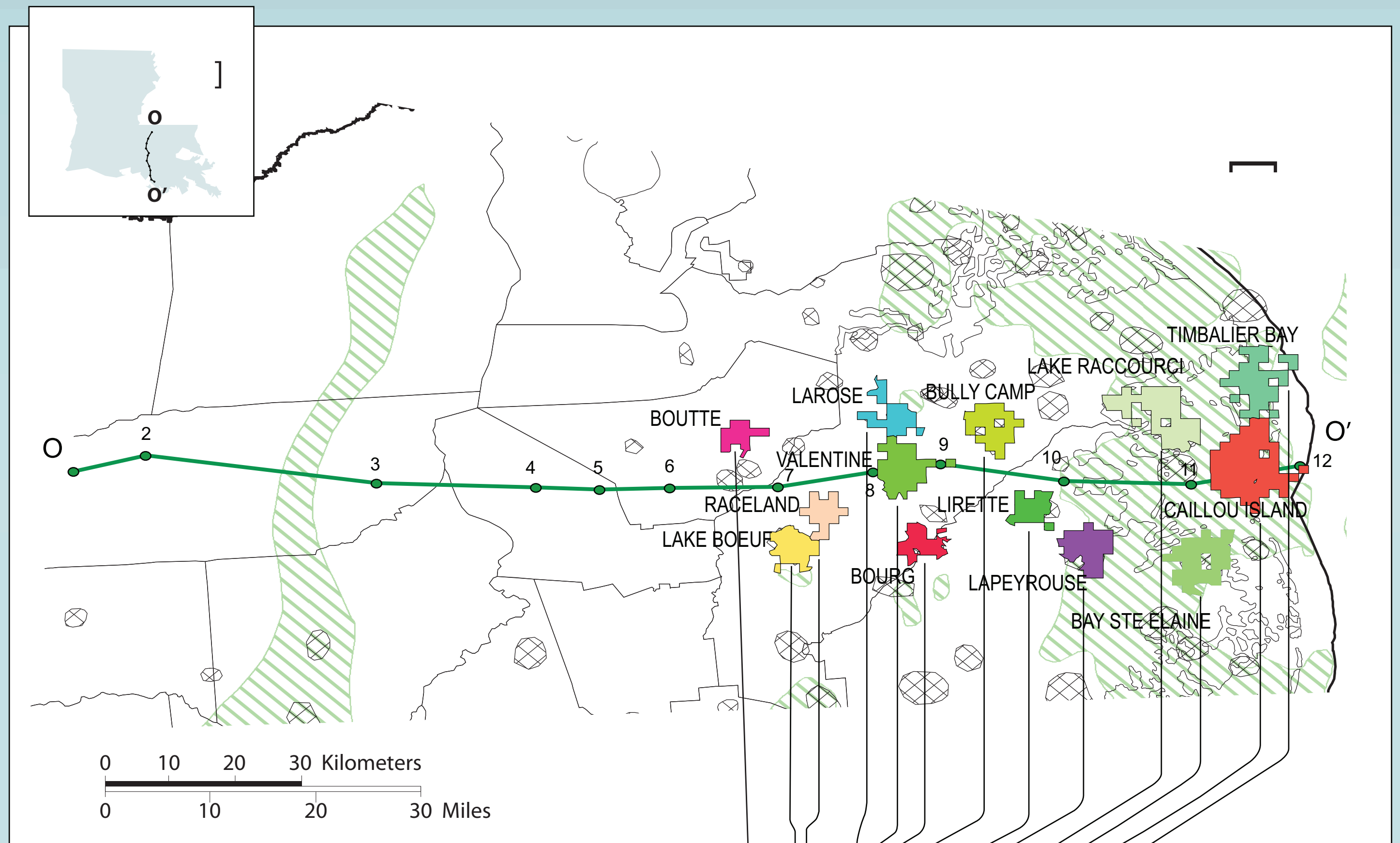


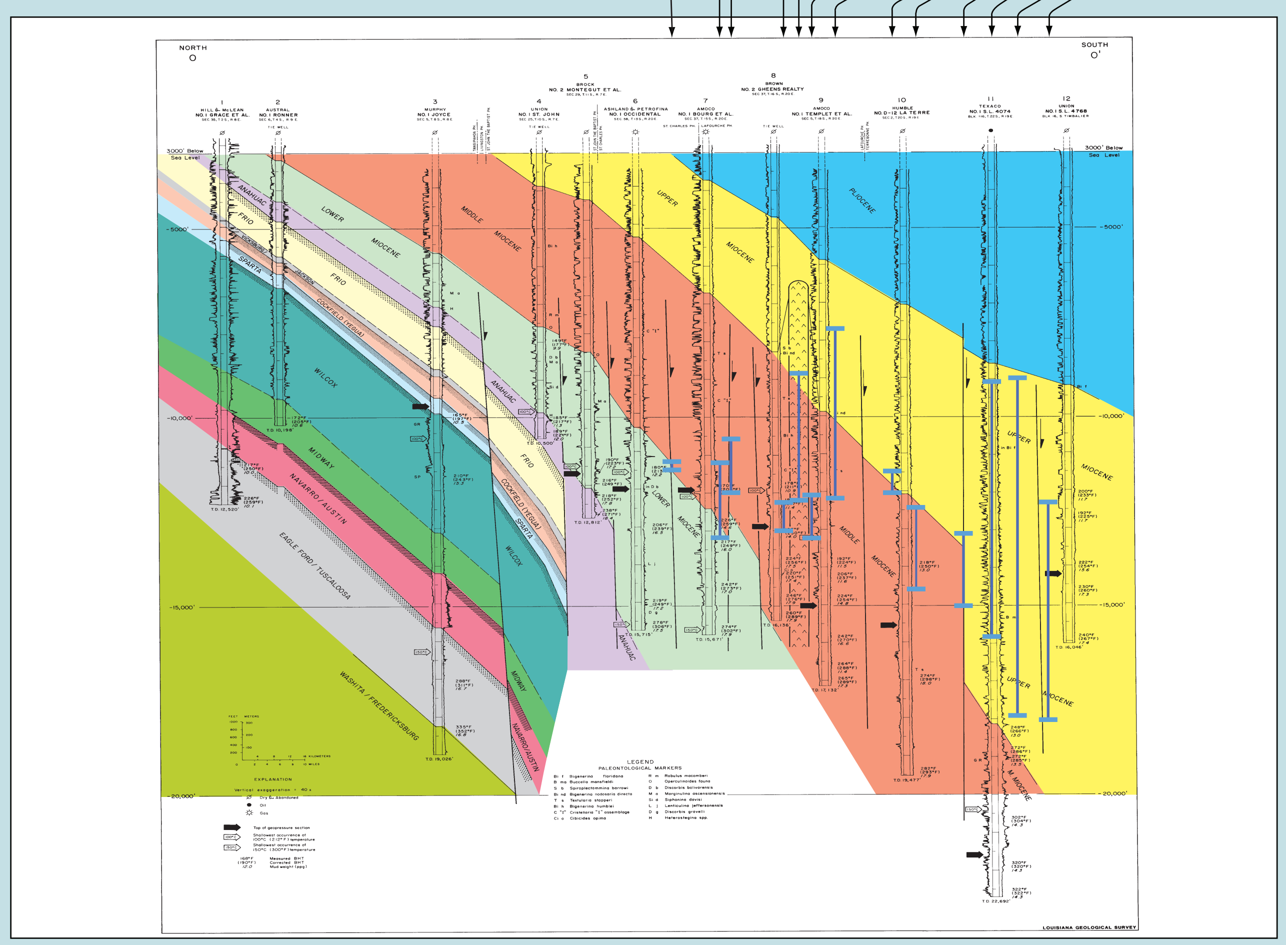


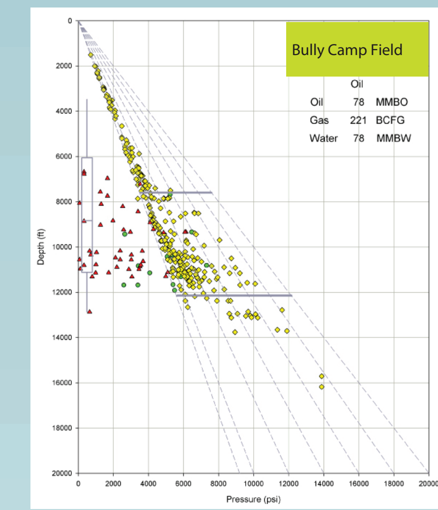


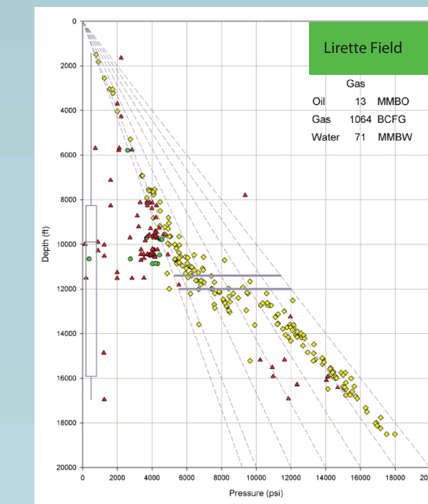


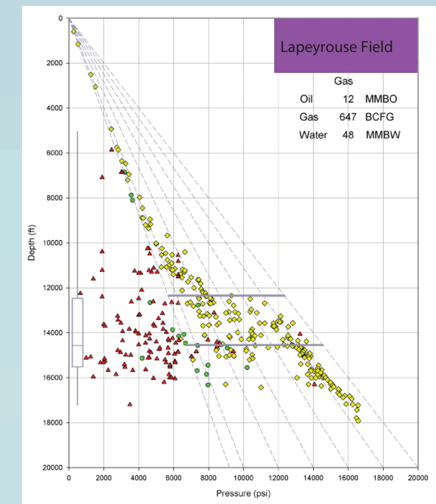


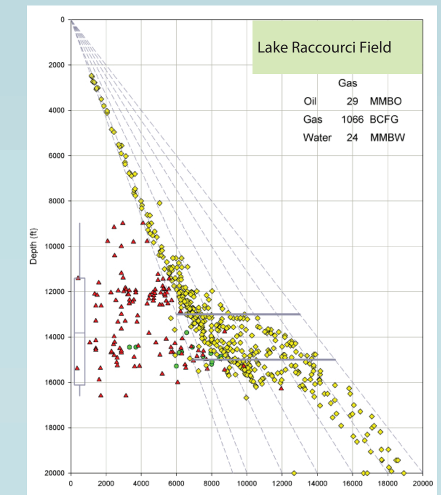


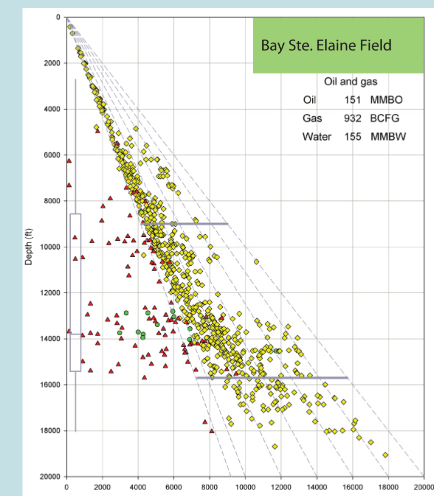


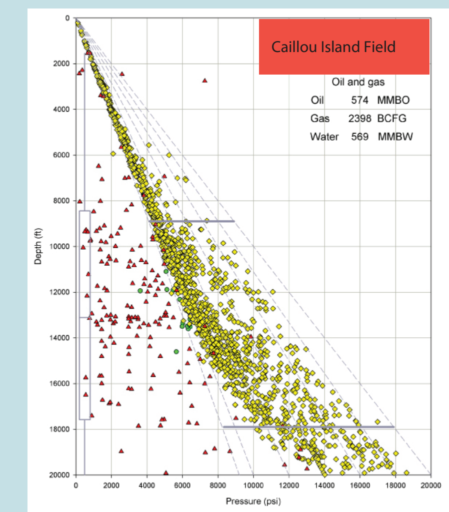


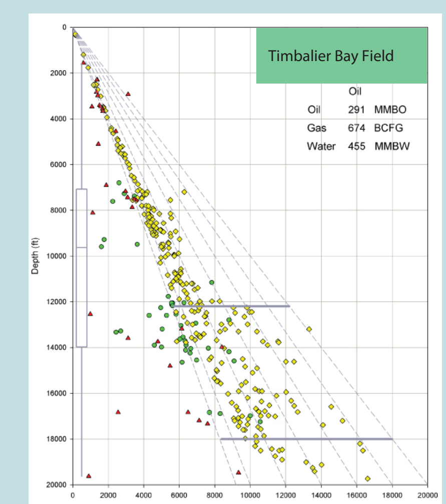












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