Waterflooding the Parks (Caddo) Field, Stephens County, Texas*

David J. Entzminger[1], Lyn Canter[1], Mark Sonnenfeld[1], and Steve Gardner[1]

Search and Discovery Article #20127 (2012)
Posted February 6, 2012

*Manuscript received December 21, 2011; accepted January 9, 2012.

[1]Whiting Petroleum Corporation, Midland Texas (entzdje@aol.com)

Abstract

Parks (Caddo) Field is located on the Bend Arch in Stephens County, Texas. It was discovered in 1916 by Texas Oil Company. The field produces from the Strawn Sands, Caddo Lime, Lake Sands, Marble Falls, and Duffer. Most of the 2.8 mmboe produced from the field has been produced from the Caddo (Pennsylvanian Strawn age) reservoir at 3200 feet.

The hydrocarbon accumulation is a part of a large combined-structural-stratigraphic trap that greatly exceeds the size of the Parks lease. The gross Caddo reservoir interval is 50-150 feet thick with an average 5% porosity and water saturation of 30%. The Caddo interval is characterized by medium- to coarse-grained, muddy, fossiliferous limestone distributed as small scale (<20 feet high) phylloid, algal buildups (or mounds) and with finer grained, subtidal limestones (intermound) deposited in a protected embayment. Pore types include secondary skeletal moldic, vug and channel pores, with lesser amounts of dolomite intercrystalline and primary interparticle.

In 2004, Whiting Petroleum Corporation (Whiting) purchased the Parks Field. Secondary oil recovery from waterflooding the Caddo Lime reservoir was seen as the upside for purchasing this 5667 acre property. The results of six other nearby Caddo Lime waterflood projects had shown that waterflooding could double the recovery from primary production.

Between 2005 and 2006, Whiting drilled 16 wells initiating five, five-spot patterns in the structural low between the southern and northern domes. Injection began in October, 2005. During the drilling program, 409 feet of conventional core were taken, modern log suites were run, wells were mudlogged, and a pre-existing 3d-seismic survey was interpreted. After reviewing 507 feet of core from four wells, a conceptual geologic model of the reservoir emerged defining the reservoir facies and porosity types. This data set reveals a mosaic of coral-phylloid algal mounds wherein the principal reservoir facies are the mound crest and mound-flanking deposits. The heterogeneity of the facies complicates waterflooding as the reservoir units appear to have limited lateral extent. In addition, the reduced oil saturation and reduced reservoir pressure, as compared to nearest waterflood unit, contributed to the suboptimal results for Whiting's waterflood.

Introduction

Parks (Caddo) Field is located on the Bend Arch in Stephens County, Texas (Figure 1). The Parks leases, operated by Whiting Oil and Gas Corporation (Whiting), produce from the Pennsylvanian Strawn Sands (Buck Creek Sands, Brandon Bridges Sands, and Lauderdale Sands), Caddo Lime, Lake Sands, Marble Falls, and Duffer. Most of the 2.8 mmboe produced from the field has been produced from the Caddo (Strawn age) reservoir at 3200 feet**.**

The lease was first drilled in 1916 by Texas Oil Company. Much of the area is officially in the "Stephens County Regular Field", but we informally refer to it as the Parks Field. Whiting's leasehold consists of four leases, the Parks A, Parks B, W.F. Houston, and W.M. Houston, which cover approximately 5557 acres (Figure 2). Texaco drilled 44 wells between 1916 and 1929. By 1934, the lease production totaled 1,803,000 bo (~40,977 bo/well). A pilot waterflood was initiated by Texaco in April, 1973, on the southern Caddo structural dome of the Parks lease. Six, 80-acre five-spot patterns were developed. It has been speculated that the dome on the south side of the property, where this pilot was performed, had developed a secondary gas cap from the early production in the field. A secondary gas cap would greatly hamper the waterflood performance, creating a voidage issue and need for a tremendous amount of water to build pressure back into the reservoir.

Whiting Petroleum Corporation purchased the property in 2004 with the intent of implementing a Caddo Lime waterflood. Table 1 shows key attributes of the Caddo Lime reservoir in the Parks lease. Numerous Caddo Lime waterfloods have succeeded throughout the county with many having a 2:1 secondary to primary production ratio**,** (unpublished engineering and geologic report). Whiting drilled 17 wells and initiated a Caddo waterflood in October 2005. Along with the core from an earlier well, Whiting took three full-diameter cores in the Caddo to help understand the reservoir architecture and distribution of productive facies.

Field Overview

A summary of the reservoir characteristics of Parks Field, as a field overview, is given in Table 1.

Parks Lease:	5667 acres
Two structural highs- with G/O Contacts	
North dome-	-1816’ ss
South dome-	-1880’ ss
O/W contact	-1990’ ss
Reservoir gross interval	50’ - 150’
Avg. Porosity	5.2% *(Cores)*
Avg. Permeability	0.42 md--geom. avg. *(Cores)*
Avg. Sw (connate)	29.6%
Avg. GOR (orig)	420 (est)
Oil Gravity	40 deg. API
Est Original Pressure	~1250 psig
Est Original Temperature	120 deg. F
Est. Original Boi	1.23
Drainage	40 ac (based on offset field analogs)

Table 1. Reservoir characteristics of Parks Field, Stephens, County, Texas.

Core Work

At least 18 cores were taken in the Caddo Lime on the Parks lease and most have core analysis, but only four cores were available for descriptve work. The routine core analysis data provided initial core-to-log (porosity and oil saturations) calibrations that appeared to be validating the OOIP numbers from the original engineering study. Therefore, it established the potential for a significant Caddo Lime waterflood target on the Parks property. The geologic model derived from core description and facies determination, pore-type definition, and depositional model construction was extended to electric-log-facies correlation field-wide. This correlation work contributed to a better understanding of the reservoir geometries and helped explain some of the waterflood performance. This is discussed in the Waterflood Development section of this paper.

Whiting cored 409 feet of Caddo. Modern log suites including induction logs, neutron-density logs, and mudlogs were run in all new wells plus some sonic logs, an image log, and sidewall cores. A 3d-seismic survey was interpreted to help provide the sequence stratigraphic framework across the lease and between wells. After reviewing 507 feet of core from four wells, a depositional model, (see Figure 3) of the Caddo Lime reservoir emerged that better defines the reservoir facies and establishes the rock-to-log correlations.

Geological Setting and Depositional Facies

A facies model was developed for the Caddo Lime reservoir that includes ten depositional facies and six petrophysical facies, Figure 4. The core porosity-permeability relationships along with log interpretations show that the best reservoir facies is Facies 8; fair-good reservoir facies are Facies 4, 7, 9, and 10, and the non-reservoir facies are Facies 1, 2, 3, 5, and 6 (Figure 5).
Facies 1 through Facies 9 are described below from deepest (Facies 1) to shallowest (Facies 9). Facies 10 is a diagenetic facies.

Laminated-Lime Mudstone (Facies 1)

The black, laminated-lime mudstone facies is devoid of allochems and is argillaceous. Thin seams of clay and stylolites are present. The porosity vs. permeability cross-plot of this facies shows it not to have pay-quality reservoir (Figure 5). This facies is interpreted as having been deposited on an outer shelf to upper slope setting. Petrophysically this facies could be lumped with Facies 2 and 3, as having high gamma ray and low-porosity characteristics (Figure 6).

Nodular-bedded Lime Mudstone (Facies 2)

The nodular-bedded lime mudstone is dark grey to black with common *Thalassinoides* burrows (Figure 6) that produce a nodular texture. It is dense, non-porous and has no reservoir potential. Its high gamma ray and low porosity character lumps it petrophysically with Facies 1 and 3.

Crinoid-Fusulinid, Lime Wacke/Packstone (Facies 3)

Facies 3 is a dark, argillaceous lime mud matrix with significantly more open marine allochems than Facies 1 and 2, including crinoids, brachiopods, and trilobite fragments (Figure 7**)**. Solution seams and stylolites are common. This facies was deposited on the outer-ramp or as storm beds in the mid-ramp. It has no reservoir potential and similar petrophysical characteristics to Facies 1 and 2. It may impact production by acting as reservoir baffles.

Burrowed, Lime Wacke/Packstone (Facies 4)

Facies 4 is a burrowed, lime wacke/packstone deposited on the middle ramp in the low-energy areas (Figure 8**)**. Grainier beds of fusulinid and foram lime wacke/packstone are slightly higher-energy, intermound deposits. The matrix is microporous in places, with poor to fair reservoir potential.

Coral Rudstone and Boundstone (Facies 5)

The coral rudstone and boundstone facies is composed of coarse fragments and in-situ skeletons of colonial corals (Figure 9**)**. These muddy, constructional buildups are dense, tan to light brown. The rudstones have a rubbly, breccia-like texture. Boundstones are rare facies only found

in the Parks #118 core. The rudstones (coral rubble) are more common and associated with phylloid algal mounds. The immense amount of mud and cemented skeletal material destroyed any porosity this facies may have had, making this a non-reservoir facies. Petrophysically this facies is characterized by low gamma ray and very low porosity and can be similar to Facies 6.

Phylloid Algal Floatstone and Boundstone (Facies 6)

One of two facies represented in the mound facies (Figure 10**)**. These floatstones or boundstones are composed of delicate flakes of phylloid algae, indicating mound construction in a low-energy setting. The mounds are dominated by a muddy matrix with rare amounts of corals, forams, and shell fragments. Matrix porosity is rare due to the high carbonate mud content. This facies has little reservoir potential, and petrophysically it is very similar to Facies 5.

Phylloid Algal-crinoid-mollusc-foram Lime Wackestone/Packstone (Facies 7)

Facies 7 is massive and composed of coarse-skeletal fragments of phylloid-algae, crinoids, molluscs and forams (Figure 11). The skeletal fragments are often partially dissolved, creating isolated molds and vugs. It has more mud content and appears to be a transitional facies into Facies 8. It is compositionally, very similar to Facies 8 but lacks the higher porosity and permeability due to the muddier matrix. The intraparticle porosity in skeletal fragments and microporosity also contributes to this facies' characteristic lower permeability. This facies is interpreted to represent interbedded mound flank and inter-mound deposits.

Plylloid Algal-crinoid-mollusc-foram Lime Packstone and Grain-dominated Packstone (Facies 8)

Interpreted as mound crest, flank and shoal deposits, Facies 8 is a packstone or grain-dominated packstone (Figure 12)**.** Common allochems include phylloid algae, crinoids, molluscs and forams. Pore types are mostly secondary skeletal molds, vugs, and solution-enhanced vugs. There is more interparticle and touching-vug porosity in Facies 8, forming the best porosity and permeability in the Parks area. This higher reservoir quality, and even oil staining makes it distinctive from Facies 7 (Figure 5).

Burrowed Lime, Mud/Wackestone (Facies 9)

Facies 9 is a muddy, lime wackestone with *Thalassonoide* burrows. Burrows can develop "chalky" reaction rims or microporous diagenetic halos that have some microporosity and can be dolomitic. Beds are usually thin to medium thick. Facies 9 is very similar to Facies 4 but lacks the digenetic halos. It is interpreted to have been deposited in a low-energy, inner ramp setting (Figure 13**).** This facies may have some patchy oil staining and is a mediocre reservoir.

Altered, Vaguely Brecciated Lime Mudstone and Wackestone (Facies 10)

Overprinting all rock types, Facies 10 is a diagenetic facies showing evidence of dissolution and local brecciation by under-saturated waters

(Figure 14**)**. It shows evidence of internal sediments and thin, earthy or "chalky" microporous beds. It may be porous or tight depending on the host rock type. Porous zones are associated with shoals and flank-shoal deposits. Petrophysically this facies is difficult to separate and seems best lumped with Facies 9.

Caddo Deposition

The Caddo was deposited on a broad, carbonate shelf upon the Concho Platform / Bend Arch between the Permian Basin on the west and Fort Worth Basin on the east (see Figure 1) (Yancey and Cleaves, 1990; Cleaves, 1993). Small phylloid algae-rich mounds became sites of sediment production and build-ups. These mounds grew up to 10-30 feet high before their growth terminated, sometimes shifting laterally into previous intermound areas, resulting in laterally discontinuous porous, reservoir facies geometries. Intermound areas are characterized by muddy facies. Episodic sea-level rise drowned the reefs. The entire Caddo is full of reefs or mounds that shifted with time throughout the Parks area. During Strawn time, fine-grained, clastic muds were deposited over a more regional area, providing correlatable shale breaks seen on the gamma ray logs within the Caddo. The black organic shale, locally called the Smithwick Shale, caps the last Caddo Lime cycle, representing a maximum transgression and providing a good reservoir seal for the Caddo Lime reservoirs (Figure 15).

Reservoir Architecture

Whiting subdivided the Caddo into 12 units. Units 6 through 12 are productive with the upper 3 units only existing in the very northern portion of the Parks lease (Figures 15 and 16**).** The reservoir architecture of the Caddo in the Parks area is a complex, mosaic of non-productive mounds and porous mound crests and flank deposits (Figure 17**)**. The areas of thicker porous, mound flank deposits define the better reservoir areas with higher pore volume. The tight and non-porous areas are most likely boundstone mounds. Calibrating the logs to core allows one to construct a pore volume map (PhiH) by zone that can be used to map the Caddo depositional facies with a fairly high degree of confidence (Figure 18).

High-frequency cycle stacking patterns and seismic stratigraphy were used to guide subsurface correlations in the Caddo Lime. High-amplitude, high-frequency sea-level changes characteristics of "icehouse" glacial eustasy complicate stratigraphic correlation. Attempts to correlate along-dip proved challenging. The facies-based geologic model was used to tie uncored wells into the high-frequency, cycle-based stratigraphy defined by the cored wells (Figure 15**).** Facies 1 and 2 represent maximum flooding surfaces (MFS), and high gamma-ray spikes representing these deeper water facies were used to subdivide flow units where present. These facies likely serve as baffles in the reservoir and impede development of consistent waterflood fronts. Twelve flow units (CDLM 1-12) were carried across the Parks area with the upper six zones being the primary productive intervals. The top three zones (10-12) are only found in the northernmost portion of the lease where it appears the carbonate system builds into a higher energy shoal environment. Lack of core in this northern area limits confirmation of this interpretation, but seismic and log work supports the interpretation. Note how to the south the reservoir units are truncated by what appears to be non-deposition, minimizing the Caddo potential to the south of the Parks lease (Figure 15).

During Caddo deposition, the Parks area appears to have been an embayment where multiple interlocking mound and intermound complexes

formed on the large-scale overall carbonate platform. The mound facies and their flanking deposits created a mosaic of interconnected reservoir with a reciprocal relationship between overlying and underlying Caddo zones (Figure 17). Even though tight mounds subdivide the zones laterally, there appears to be enough flank, mound crest and grainy intermound facies to connect the reservoir. This interpretation was validated during Whiting's 2005-06 development program. These new wells encountered low bottom-hole pressure (<300 psi) compared to original formation pressure of approximately 1250 psi.

Unfortunately, neither the reservoir model nor architecture work was completed prior to drilling to help guide well locations or patterns. This enhanced understanding of the reservoir architecture and flow units suggests limited waterflood potential and will limit future Caddo drilling to areas of better reservoir quality and oil saturation as defined by the mapping.

Field Development

Texaco had injected 57 mmbw into six, five-spot patterns and only recovered a little over 200 mbo on the south dome of the Parks lease. It had been reported that the reason for the poor performance of the Texaco flood was a secondary gas cap created by all the early production from the 1920's to the 1940's. This would have created an enormous fill-up challenge along with a greatly reduced oil saturation in the area. To avoid the dismal performance Texaco had with their flood, Whiting decided to initiate its flood in the structural trough between the north and south domes on the Parks Lease where there had been some good early producers (Figure 2).

In 2005 and 2006, seventeen wells were drilled by WOG which included six full five-spot patterns. Several producers were tested soon after they were drilled, but there was little to no oil recovery as the bottom-hole pressures were less than 300 psi, much lower than expected. Even though there had been very few wells in this area it became apparent that the old 1920 era wells had depleted the reservoir over a significant area. Water injection was introduced at 300 bwpd in each injector to help create what was hoped to be an even water distribution and avoid over-injection causing water to go out of zone. All porosity in units six through nine was perforated to help connect reservoir between injectors and producers (Figure 17). Waterflood response was expected in 12-18 months. Patterns V and S were first to get water injection in mid-2005 followed by the other three patterns in early 2006 (Figures 19). As pressure built up in the injectors, the center producer was put on production. Oil increased fairly rapidly in early 2006 but quickly flattened. Most of these producers performed below expectations, except the Parks 125 (Figure 20), which showed a good response in early 2007. Eventually, a sub-pump was installed in order to reduce the high fluid level in the Parks 125, the producer in pattern D. This well peaked at over 50 bopd, while the other producers were making less than 10 bopd. Additional water was redirected to pattern D to maintain the production and pressure support. By 2007, water produced was equal to water injected. Due to a lack of adequate surface facilities, insufficient water was available for the other waterflood patterns.

After four years of injecting water, only our easternmost pattern D, in the structurally lowest part of the field, has produced respectably. One hypothesis for the better performance of Pattern D is that, concurrent with forming the secondary gas cap in the Parks area, oil was forced to the structurally lowest area due to gravity drainage (Figure 2). Unfortunately, the Caddo isochore map of oil-saturated pore volume (SoPhiH) does not support this hypothesis.

Waterflood Performance

One obvious difference between the successfully waterflooded NW Breckenridge Waterflood Unit (immediately offsetting the Parks to the northwest) and Parks area is a greater development of Caddo Lime units 9-12. These units double the amount of reservoir quality facies. This contributes to the greater SoPhiH and more potential for waterflood recovery.

Even though the lack of adequate facilities and lack of additional water supply have hampered the Caddo Lime waterflood, it may be the reservoir quality and past production practices (no reservoir pressure maintenance) that most affected the waterflood potential for the Parks area. Oil/water relative permeability curves suggest small increases in water saturation can result in rapid increase in water mobility and less oil (Weiss and Baldwin, 1985). Based on other waterfloods in the area and the responses we have seen, it is not uncommon to see lots of water injected into the Caddo Lime to move the remaining oil, an approach informally termed “drag-flooding”.

The current understanding of the Caddo reservoir limits the area on the Parks lease that might be prospective for an economic waterflood. Future wells need to target areas to the west and southwest of the current patterns to maximize the potential for reservoir quality (SoPhiH) and structural elevation. The northernmost area of the Parks lease would gain reservoir quality, but the secondary gas cap in that area may doom the chance for a successful waterflood. The southernmost Parks lease has minimal reservoir and much was condemned by the old Texaco pilot flood that was situated on the southern high. The central portion of the Parks area still has potential; however, expanding the infrastructure at Parks to handle and acquire the large amounts of water is still being reviewed for economic profitability.

Conclusion

The insights from the core work provide an understanding of the reservoir architecture, pore networks, and flow units within the Caddo at Parks Field. It is this foundation that gives some context to areas with better reservoir development and economic waterflood potential. The geological framework, production performance, and operational understanding will guide any future waterflood expansion. In the end, it may be oil prices and operational costs that will ultimately decide the destiny of the Parks lease for Whiting.

References

Brown, L.F., Jr., R.F. Solis-Iriarte, and D.A. Johns, 1990, Regional Depositional Systems Tracts, Paleogeography, and Sequence Stratigraphy, Upper Pennsylvanian and Lower Permian Strata North and West-Central Texas: Bureau Economic Geological Report of Investigations No. 197, p. 1-112.

Brown, L.F., 1973a, Pennsylvanian rocks of north-central Texas: an introduction in L.F. Brown Jr., et al., Pennsylvanian Depositional Systems in North-Central Texas: University Texas Austin, Bureau Economic Geological Guidebook 14, p. 1-9.

Brown, L.F., 1973b, Cratonic basins: terrigenous clastic models, in L.F. Brown Jr., et al., Pennsylvanian Depositional Systems in North-Central Texas: University Texas Austin, Bureau Economic Geological Guidebook 14, p. 10-30.

Cleaves, A.W., 1993, Sequence stratigraphy, systems tracts, and mapping strategies for the subsurface Middle and Upper Pennsylvanian of the eastern shelf, *in* AAPG Southwest Section Regional Meeting: Fort Worth Geological Society, p. 26–42.

Cleaves, A.W., II, and A.W. Erxleben, 1985, Upper Strawn and Canyon cratonic deposition of the Bend Arch, North-Central Texas, *in* C.J. McNulty, and J.G. McPherson, (eds.), Transactions: AAPG Southwest Section: p. 27-46.

Coughran, T., 1989, Seismic Reflection Surveying for Oil and Gas Fields, in North Central Texas: Ft. Worth Geological Society, A Symposium on the Petroleum Geology of Mississippian Carbonates in North Central Texas, November 18, 1989, p. 117-150.

Erxleben, A.W., and A.W. Cleaves, 1985, Strawn-Canyon Depositional Systems, North-Central Texas: AAPG SW Section Meeting, Middle & Upper Pennsylvanian Cratonic Basin Facies Models, North-Central Texas, p. 1-12.

Esgen, W.K., 1929, Relation of Accumulation of Petroleum to Structure in Stephens County, Texas, *in* S. Powers, J.P.D. Hull, J.V. Howell, and A.W. McCoy, (eds.), Structure of Typical American Oil Fields: A Symposium on the relation of oil accumulation to structure: AAPG Special Publications, Volume II, p. 470-479.

Hasan, S.M., 1974, Curry Unit: A Successful Waterflood in a Depleted Carbonate Reservoir with High Gas Saturation: Journal Petroleum Technology, p. 1359-1364.

Manrique, E.J., V.E. Muci, and M.E. Gurfinkel, 2006, EOR Field Experiences in Carbonate Reservoirs in the United States: SPE 100063, SPE Reservoir Evaluation & Engineering, v. 10/6, p. 667-686.

Turner, G.L., 1957, Paleozoic stratigraphy of the Fort Worth basin, *in* F.B. Conselman, (ed.), The Lower Pennsylvanian and Mississippian Rocks of the North-East Llano Uplift: Abilene and Fort Worth Geological Joint Guidebook, p. 57-77.

Weiss, W.W., 1992, Performance Review of a large-scale polymer flood: SPE/DOE 24145, p. 437-450.

Weiss, W.W., and R.W. Baldwin, 1985, Planning and implementing a large-scale polymer flood: Journal of Petroleum Technology, p. 720-730.

Yancey, T.E., and A.W. Cleaves, II, 1990, Carbonate and siliciclastic sedimentation in late Pennsylvanian cycles, North-Central Texas, *in* T.E. Yancey, A.W. Cleaves, II, and M.K. Nestell, Carbonate and siliciclastic sedimentation in late Pennsylvanian cycles, North-Central Texas: Geological Society of America Annual Meeting, Field Trip No. 7: Dallas Geological Society, p. 1-20.

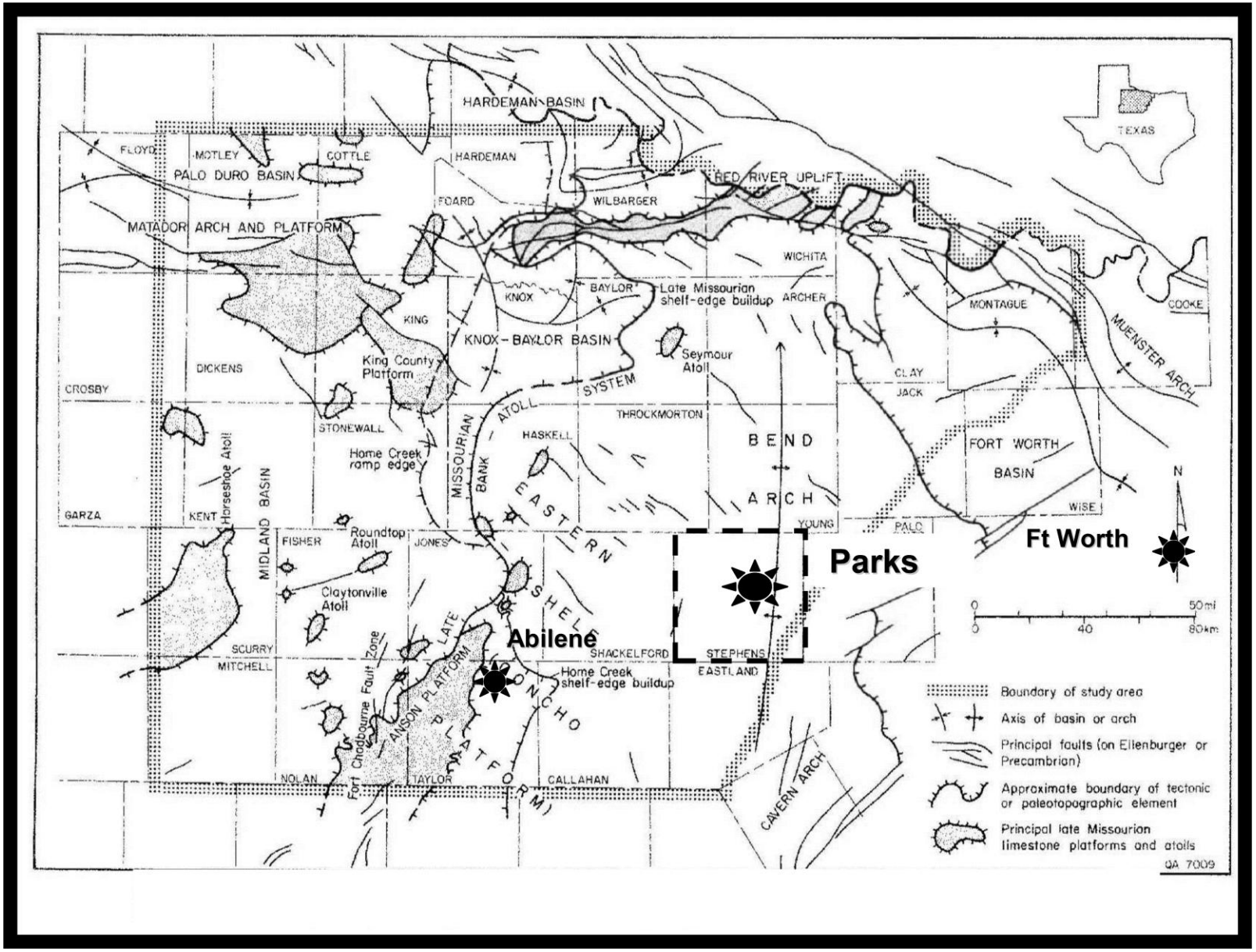


Figure 1. Paleographic map of the eastern portion of the Permian Basin, Fort Worth Basin, and Eastern Shelf of Texas (highlighted is the Parks field location) (modified from Brown, 1990).

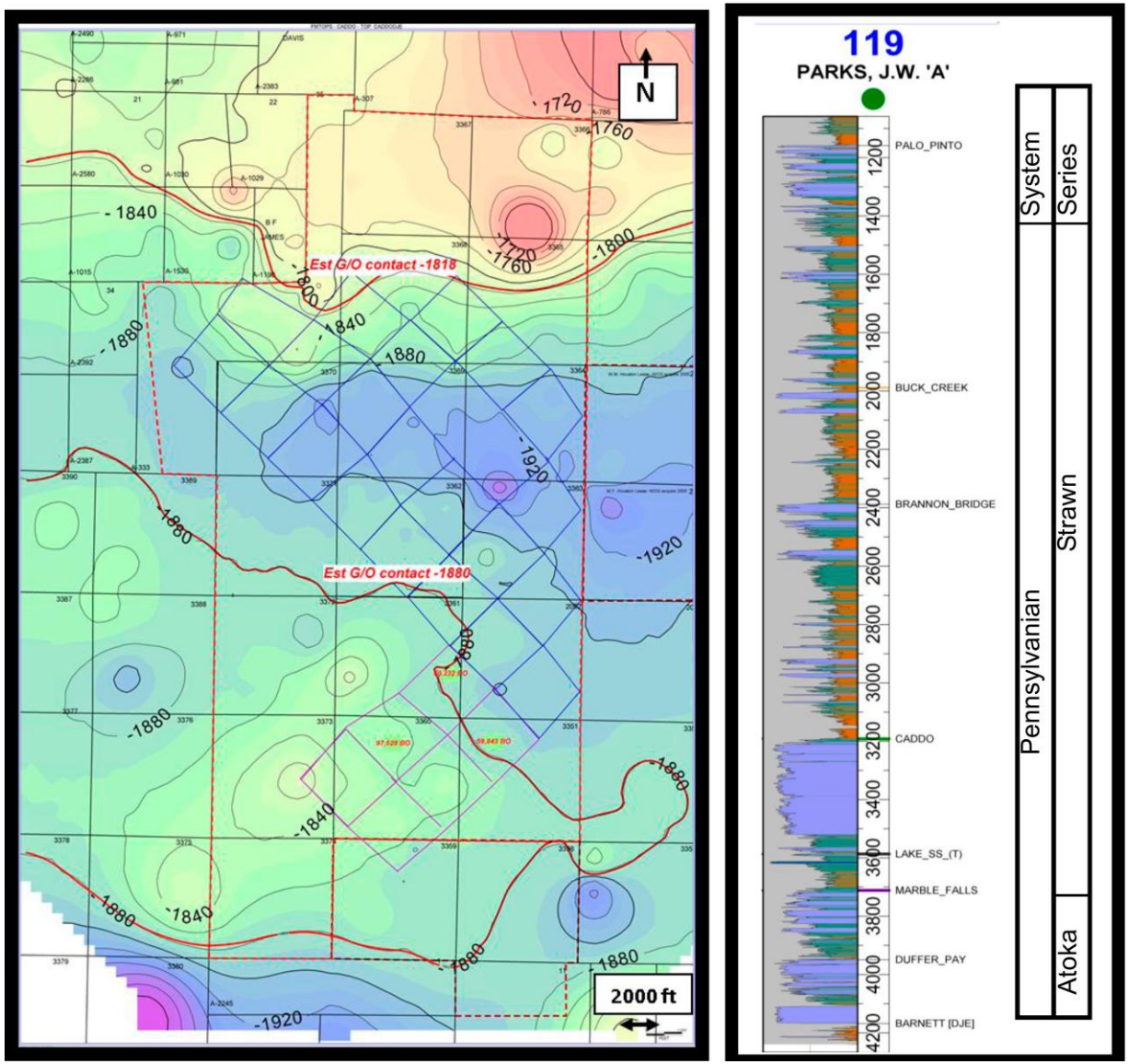


Figure 2. Structure map on top of the Caddo Limestone (contour interval 20 ft) with cool colors as lows and warm colors as highs. Dashed red line outlines Whiting Oil and Gas Company's leases in Parks Area of Stephens County, Texas. Purple diamond patterns are the six, five-spot waterflood patterns by Texaco. Blue diamond patterns are the current and proposed five-spot waterflood patterns by Whiting. Type log showing key formation or marker tops.

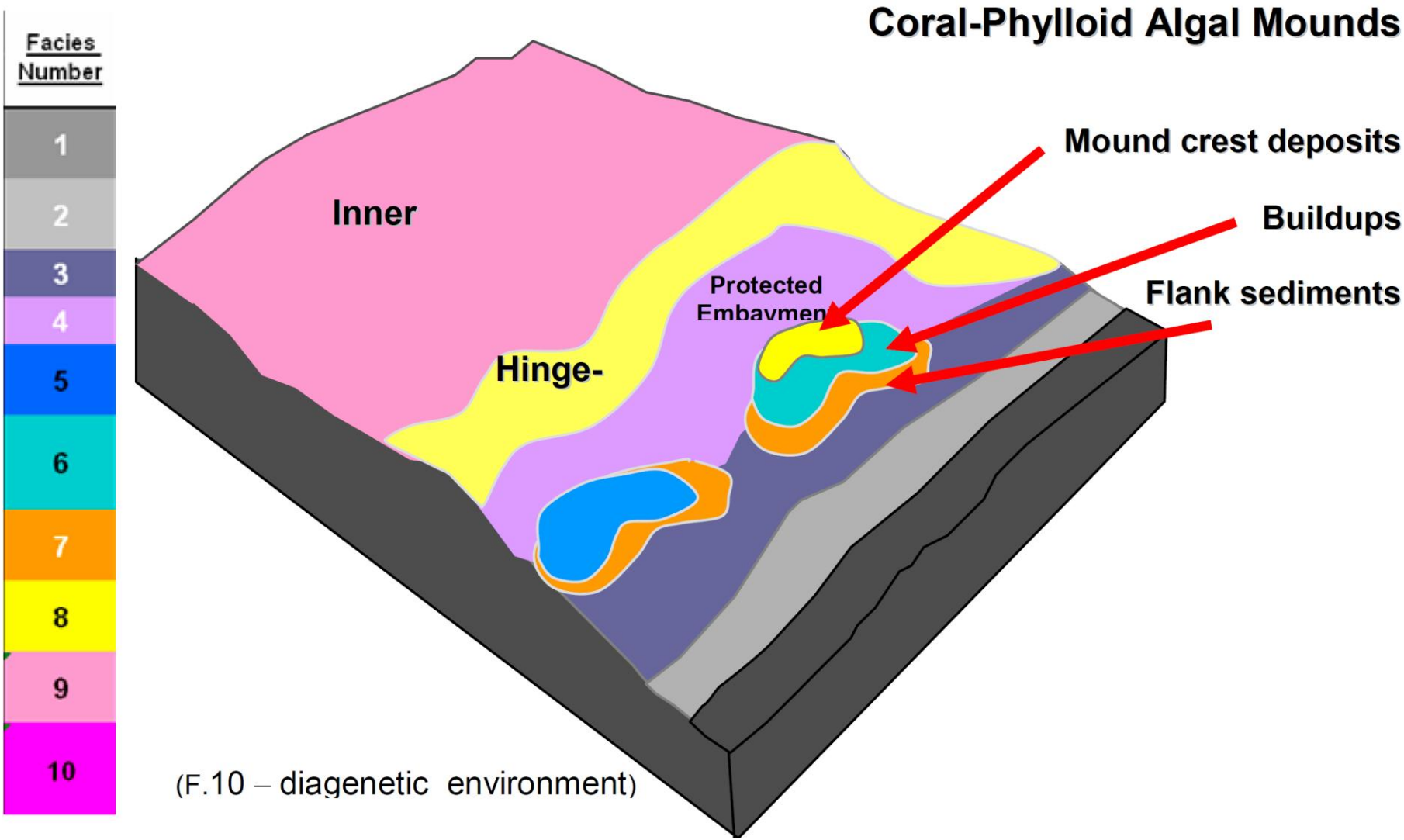


Figure 3. Idealized Caddo depositional model with algal mounds in protected embayment.

Pay?	Possible Petrophysical Groupings + PFacNum	Facies Number	Description	Interpretation	Comments
non-reservoir	g1	1	**Laminated lime mudstone:** dark gray to black, argillaceous, clay seams and low amplitude stylolites common, may contain <1cm horizontal burrows	flooding facies in outer-ramp to slope setting	dense, non-porous, NO stain
non-reservoir		2	**Nodularly bedded/burrowed lime mudstone:** dark gray to black, 2-D *Thalassinoides* burrows common (*Thalassinoides horizontalis?*), may contain scattered crinoids, brachiopods, and/or forams	flooding facies in outer-ramp to slope setting, possibly with firm grounds	dense, non-porous, NO stain
non-reservoir		3	**Crinoid-fusulinid lime wacke/packstone:** thin beds, dark to medium gray, wavy bedded to homogeneous	outermost ram-/upper slope; storm beds in mid-ramp	isolated MO and WP pores; tight, typically argillaceous lime mud matrix
mediocre reservoir facies	*g2*	4	**Burrowed lime mud/wackestone:** 3-D *Thalassionoides*-burrowed, thin-medium bedded	low energy middle ramp, intermounds	minor microporosity in matrix, rare secondary pores
non-reservoir	*g3*	5	**Coral rudstone and boundstone:** coarse fragments and possible *in situ* skeletons of colonial corals, tan to light brown, dense, rudstones have a rubbly/breccia-like texture	muddy constructional buildups	rare facies, present only in the Parks #118 core, associated with phylloid algal material, rare matrix porosity
non-reservoir		6	**Phylloid algal floatstone and boundstone:** mostly delicate forms of phylloid algae indicate low energy setting, abundant mud matrix (mound core subfacies), rare corals, forams, and shell fragments, argillaceous in places	muddy constructional buildups	rare matrix porosity due to high carbonate mud content
fair reservoir facies	g4	7	**Phylloid algal-crinoid-mollusc-foram lime wackestone and packstone:** massive, coarse skeletal fragments are partly dissolved	interbedded mound flank and intermound deposits	low perm, facies, mostly secondary pores such as isolated molds and vugs some intraparticle porosity in chambered skeletal fragments, minor patchy oil stain
main reservoir facies	g5	8	**Phylloid algal-crinoid-mollusc-foram lime packstone and grain-dominated packstone:** massive, associated with muddier interbeds (intermound deposits)	mound crest, flank, and shoal deposits	best porosity and permeability overall, mostly secondary pores (vugs, molds and micropores), mostly even oil staining
mediocre reservoir facies	g6	9	**Burrowed lime mud/wackestone:** 3-D Thalassionoides-burrowed, thin-medium bedded, "chalky" reaction rims / diagenetic halos around burrows	low energy inner ramp, possible up-dip subaerial exposure	minor microporosity in burrow halos; some microporosity in matrix, possible dolomitic, patchy oil staining
good reservoir facies		10	**Altered, vaguely brecciated lime mudstone and wack/packstone:** strong evidence of dissolution and local brecciation by carbonate undersaturated waters, "chalky" microporous thin beds, possible internal sediment	short-term subaerial exposure	"chalky" microporous thin beds cap HFC, most common in lower cycle in the Parks #118 core, oil-stained

Figure 4. Caddo facies table corresponding to the depositional model in Figure 3.

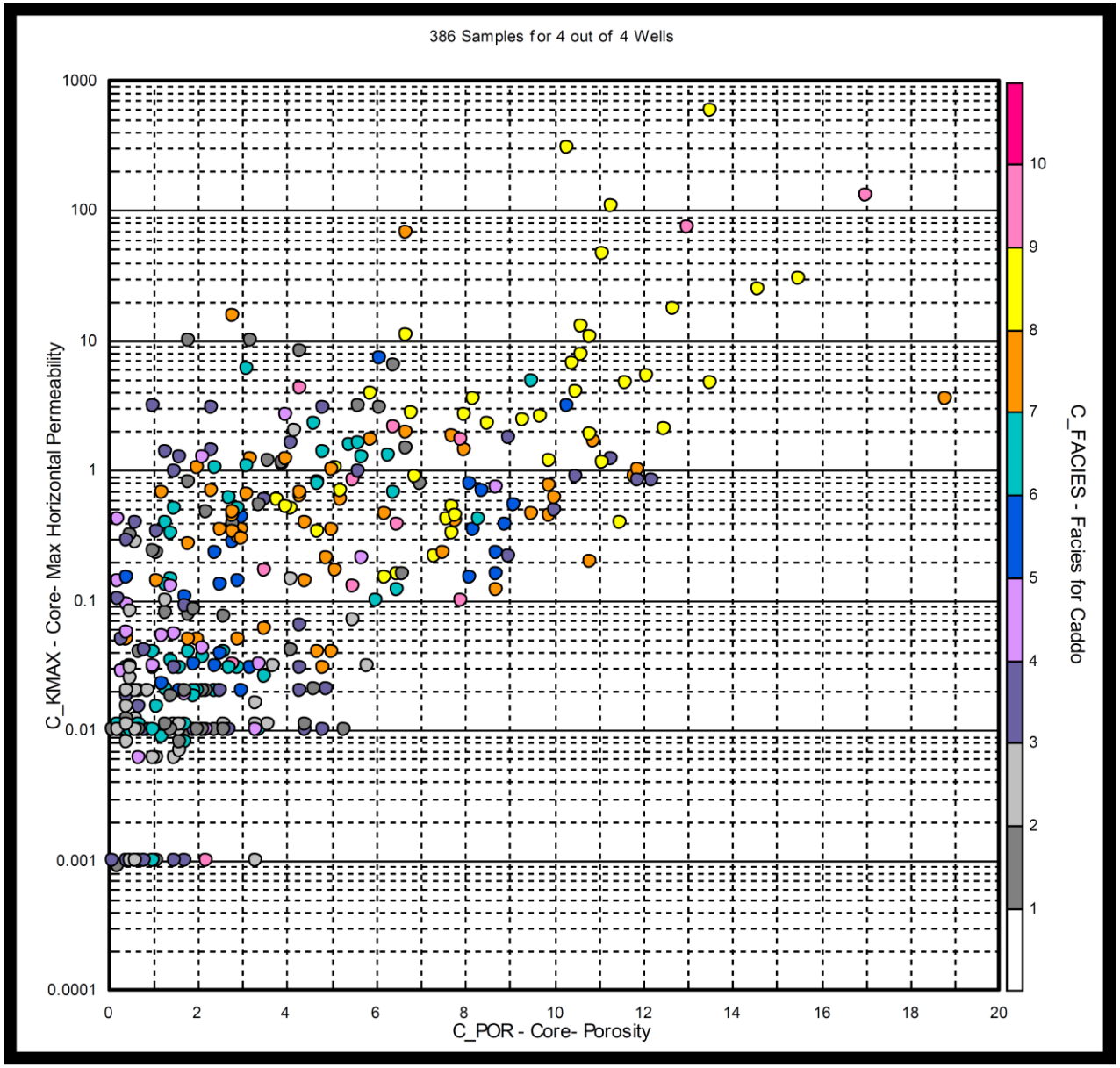
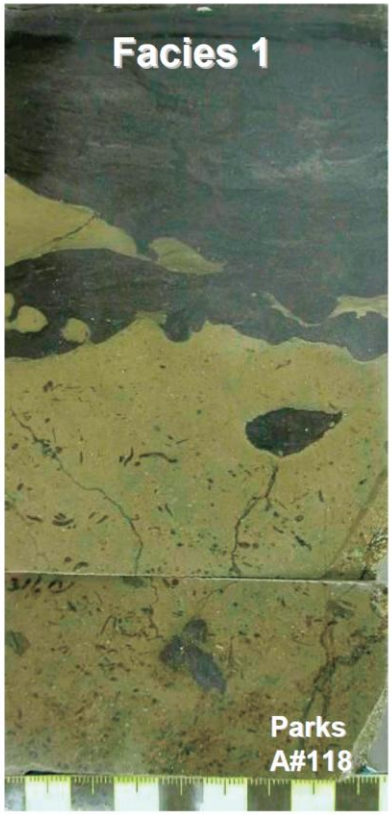
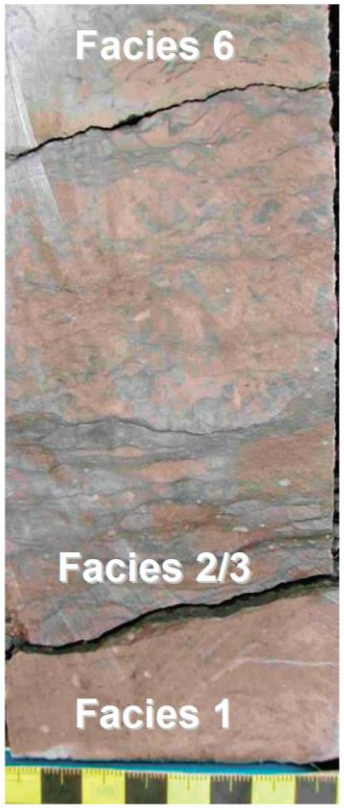


Figure 5. Core porosity vs. permeability cross-plot, color-coded with the Caddo facies for the four wells with core descriptions. The higher porosity and permeability characteristics of Facies 8 (yellow circles) are easily seen, as cross plotted along with the other facies.

Facies 1 and 2

Pay?	Possible Petrophysical Groupings = PFacIlum	Facies Number	Description	Interpretation	Comments
non-reservoir		1	**Laminated lime mudstone;** dark gray to black, argillaceous, clay seams and low amplitude stylolites common, may contain <1cm horizontal burrows	flooding facies in outer-ramp to slope setting	dense, non-porous, NO stain,
non-reservoir	g1	2	**Nodularly bedded / burrowed lime mudstone;** dark gray to black, 2-D *Thalassinoides* burrows common (*Thalassinoides horizontalis*?), may contain scattered crinoids, brachiopods, and/or forams	flooding facies in outer-ramp to slope setting, possibly with firm grounds	dense, non-porous, NO stain,





MFS units typically have sharp bases and tops

Facies 1 is devoid of allochems

Solution seams and stylolites

Nodules in Facies 2 probably after horizontal burrows

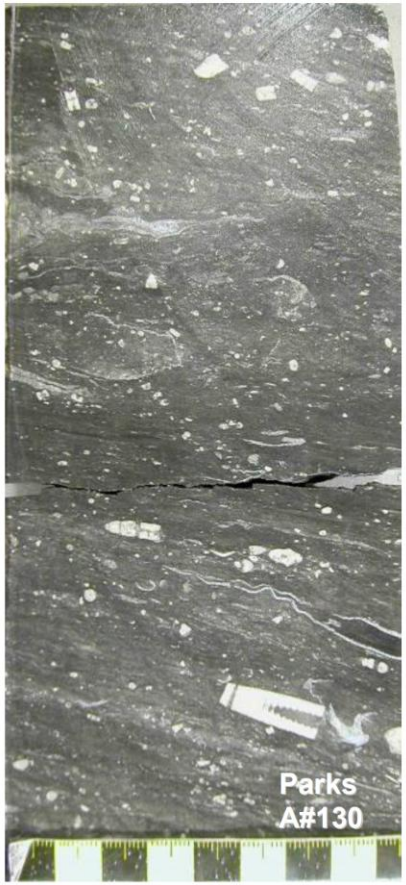
Rare allochems in Facies 2

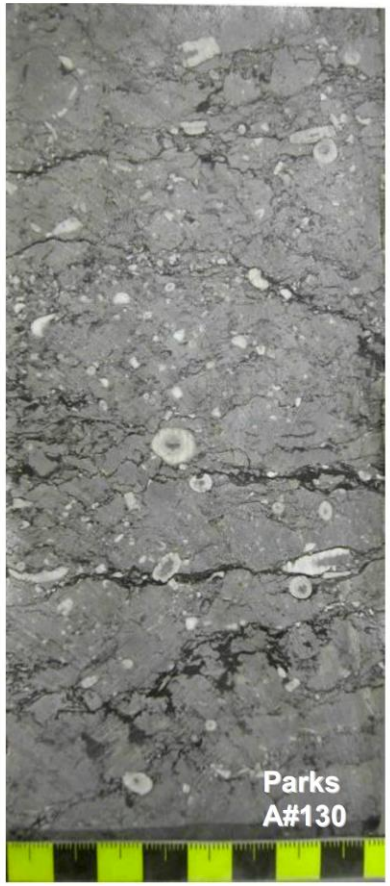
No reservoir potential; source rock potential is unknown

Figure 6. Caddo, Facies 1: Laminated-lime mudstone; also Caddo Facies 2: Nodular-bedded lime mudstone (non-reservoirs).

Facies 3

Pay?	Possible Petrophysical Groupings = PFacNum	Facies Number	Description	Interpretation	Comments
non-reservoir		3	**Crinoid-fusulinid lime wacke/packstone;** thin beds; dark to medium gray, wavy bedded to homogeneous	outermost ramp/upper slope; storm beds in mid-ramp	isolated MO and WP pores; tight, typically argillaceous lime mud matrix





Argillaceous dark lime mud matrix is similar to that of Facies 1 & 2

Facies 3 contains significantly more open marine allochems: Crinoids, brachiopods, trilobite fragments are common

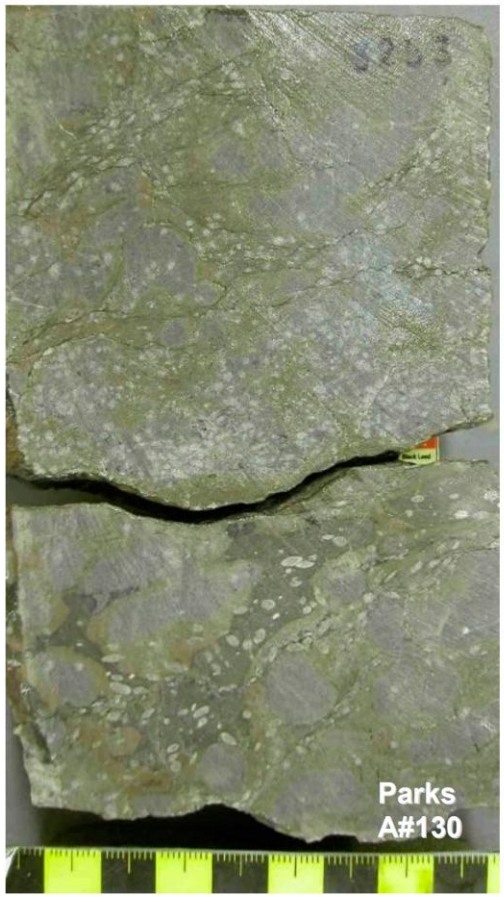
Solution seams and stylolites

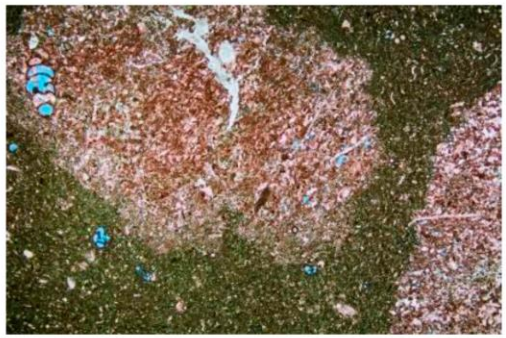
No reservoir potential; source rock potential is unknown

Figure 7. Caddo, Facies 3: Crinoid-fusulinid lime wacke/packstone (non-reservoir).

Facies 4

Pay?	Possible Petrophysical Groupings = PFacIlum	Facies Number	Description	Interpretation	Comments
mediocre reservoir facies	*g2*	4	**Burrowed lime wacke/packstone;** 3-D *Thalassionoides*-burrowed, thin-medium bedded, common fusulinids, forams	low energy middle ramp, intermound and storm beds	minor microporosity in matrix, rare secondary pores





Thin Section

Parks A#130 3258' 20X

Mostly wackestones and wacke/packstones

Grainier beds are likely storm deposits

3-D *Thalassinoides* burrows common

Fusulinids are most common allochems, rare peloids, crinoids, molluscs

Matrix is microporous in places, poor to fair reservoir potential

Figure 8. Caddo, Facies 4: Burrowed lime wacke/packstone (mediocre reservoir).

Facies 5

Pay?	Possible Petrophysical Groupings = PFacIlum	Facies Number	Description	Interpretation	Comments
non-reservoir		5	**Coral rudstone and boundstone;** coarse fragments and possible *in situ* skeletons of colonial corals, tan to light brown, dense, rudstones have a rubbly/breccia-like texture	muddy constructional buildups	rare facies, present only in the Parks #118 core, associated with phylloid algal material, rare matrix porosity

Boundstones are rare, rudstones or coral rubble, is more common

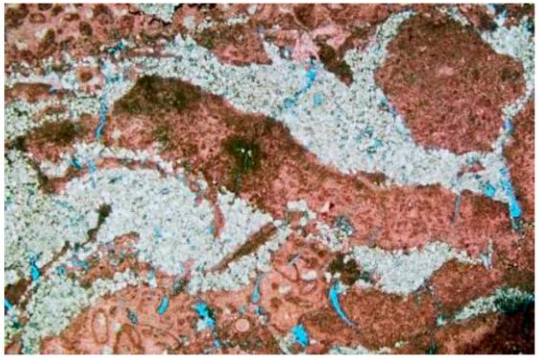
Associated with phylloid algal mounds (corals are pioneering colonizers)

Generally part of a low porosity and permeability mud mound

Figure 9. Caddo, Facies 5: Coral rudstone and boundstone (non-reservoir).

Facies 6

Pay?	Possible Petrophysical Groupings = PFacIlum	Facies Number	Description	Interpretation	Comments
non-reservoir	*g3*	6	**Phylloid algal floatstone and boundstone;** mostly delicate forms of phylloid algae indicate low energy setting, abundant mud matrix (mound core subfacies), rare corals, forams, and shell fragments, argillaceous in places	muddy constructional buildups	rare matrix porosity due to high carbonate mud content



Thin Section

Parks A#118 3181' 40X

Mostly floatstones constructed by delicate forms of platy algae

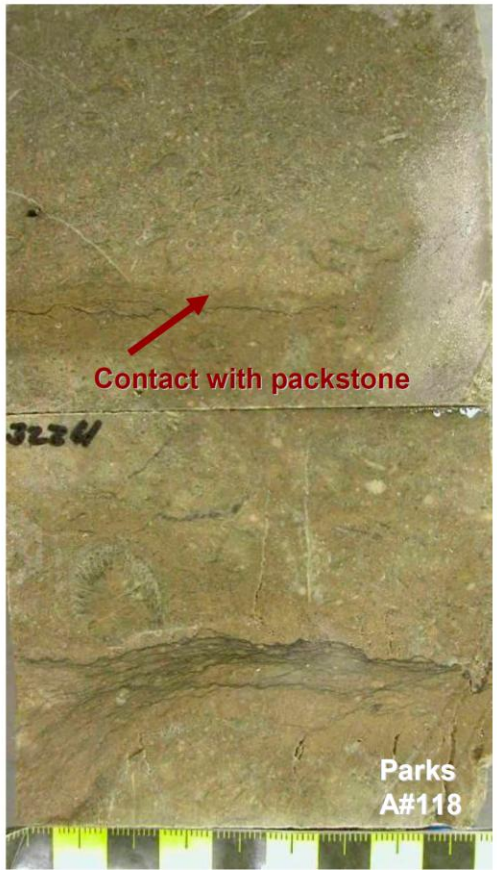
Sheltered areas underneath algal plates filled with carbonate mud and/or fine skeletal fragments

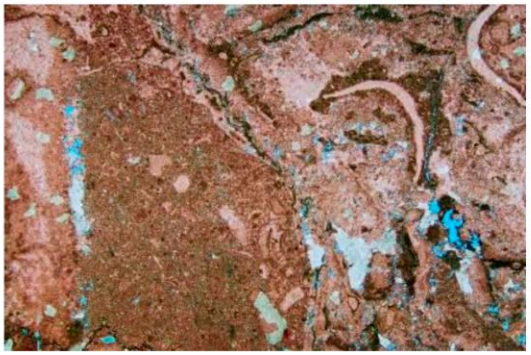
Generally part of a low porosity and permeability mud mound; but may have secondary moldic porosity, scattered vugs, and channel pores

Figure 10. Caddo, Facies 6: Phylloid algal floatstone and boundstone (non-reservoir).

Facies 7

Pay?	Possible Petrophysical Groupings + PFacNum	Facies Number	Description	Interpretation	Comments
fair reservoir facies	g4	7	**Phylloid algal-crinoid-mollusc-foram lime wackestone and packstone:** massive, coarse skeletal fragments are partly dissolved	interbedded mound flank and intermound deposits	low perm, facies, mostly secondary pores such as isolated molds and vugs some intraparticle porosity in chambered skeletal fragments, minor patchy oil stain





Thin Section

Parks A#118 3203' 20X

Mostly wacke/packstones

Common allochems include phylloid algal fragments, molluscs, peloids, crinoids, and forams

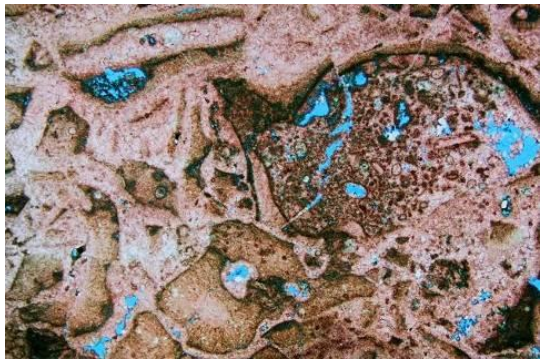
Transitional facies – mound to intermound, distal shoal

Muddy wacke/packstones are microporous in places, poor to fair reservoir potential, whereas grain-rich packstones have minor to common secondary pores and rare primary pores

Figure 11. Caddo, Facies 7: Phylloid algal-crinoid-mollusc-foram lime wackstone / packstone (fair reservoir).

Facies 8

Pay?	Possible Petrophysical Groupings = PFacNum	Facies Number	Description	Interpretation	Comments
main reservoir facies	g5	8	**Phylloid algal-crinoid-mollusc-foram lime packstone and grain-dominated packstone;** massive, associated with muddier interbeds (intermound deposits)	mound crest, flank, and shoal deposits	best porosity and permeability overall, mostly secondary pores (vugs, molds and micropores), mostly even oil staining



Thin Section

Parks A#118
3232'
20X

Mostly packstones and rare grain-dominated packstones

Common allochems include phylloid algal fragments, molluscs, peloids, crinoids, and forams

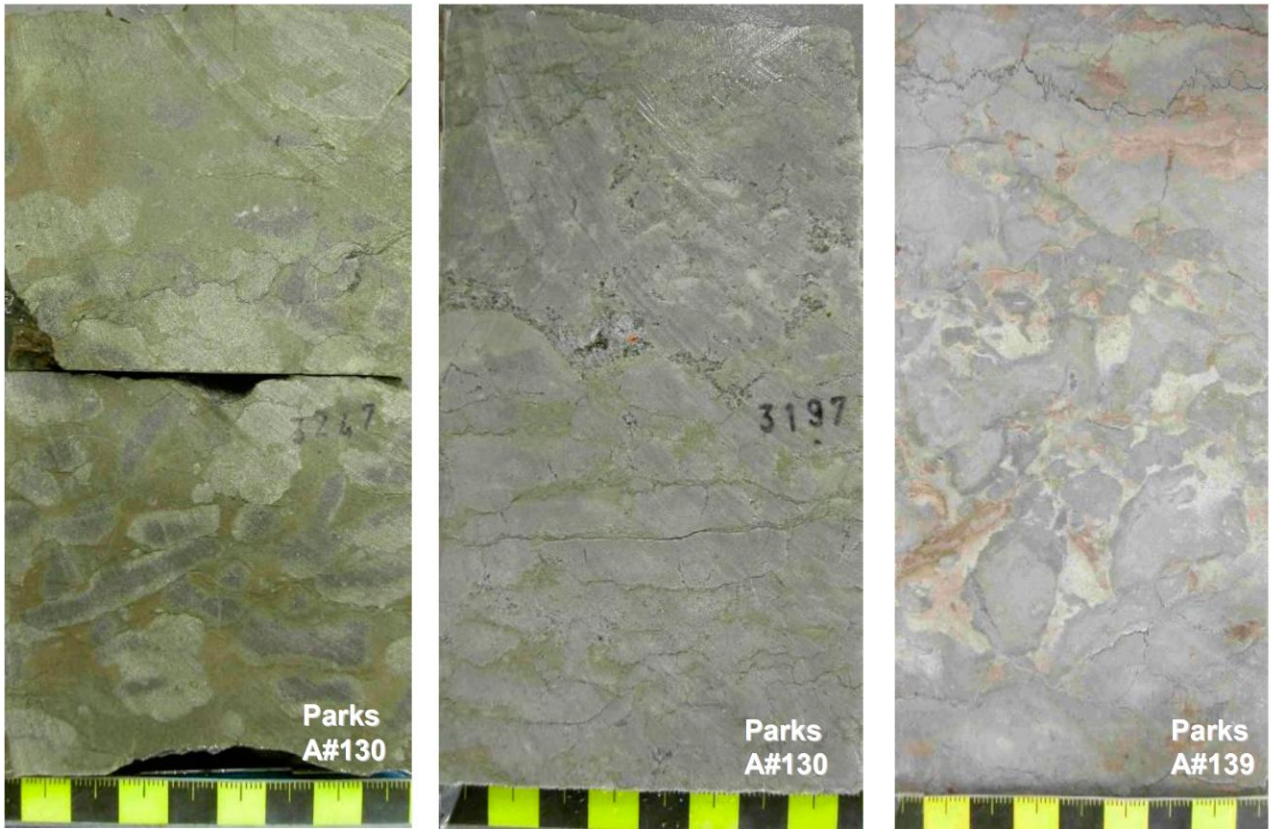
Pore types are mostly secondary skeletal molds, vugs, and solution-enhanced vugs and short discontinuous microfractures, minor interparticle pores

Good reservoir potential with patchy to even oil staining

Figure 12. Caddo, Facies 8: Phylloid algal-crinoid-mollusc-foram Lime Packstone and Grain-dominated Packstone. (Main reservoir).

Facies 9

Pay?	Possible Petrophysical Groupings = PFacIlum	Facies Number	Description	Interpretation	Comments
mediocre reservoir facies		9	**Burrowed lime mud/wackestone;** 3-D *Thalassionoides*-burrowed, thin-medium bedded, "chalky" reaction rims / diagenetic halos around burrows	low energy inner ramp, possible up-dip subaerial exposure	minor microporosity in burrow halos; some microporosity in matrix, possibly dolomitic, patchy oil staining



Mostly mudstones and mud/wackestones

3-D *Thalassinoides* burrows common

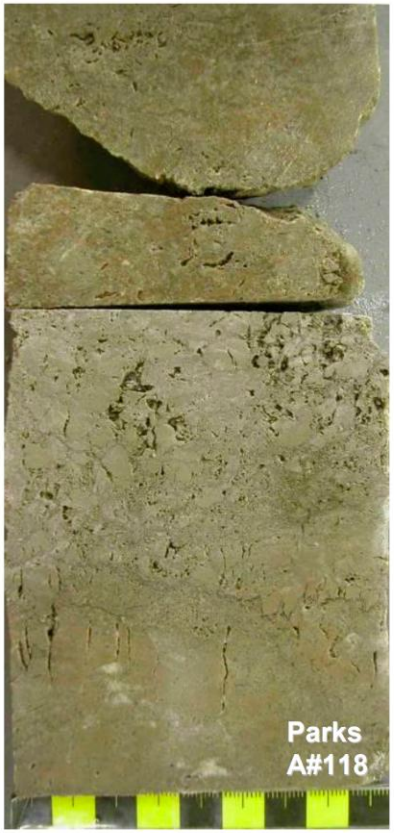
Diagenetically altered facies – burrows have reaction halos around perimeter, mud matrix has a dull, earthy "chalky" textures

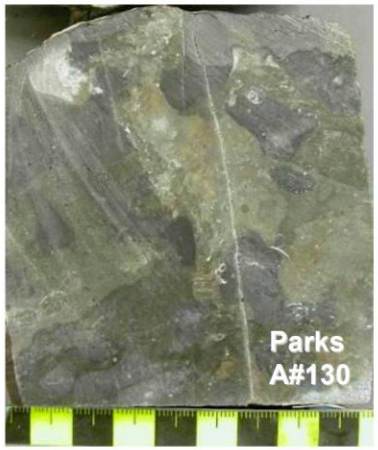
Mud matrix is microporous in places, fair reservoir potential, minor patchy oil stain

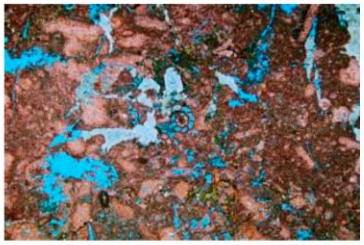
Figure 13. Caddo, Facies 9: Burrowed lime mud/wackestone (main reservoir).

Facies 10

Pay?	Possible Petrophysical Groupings = PFacNum	Facies Number	Description	Interpretation	Comments
good reservoir facies	g6	10	**Altered, vaguely brecciated lime mudstone and wacke/packstone;** strong evidence of dissolution and local brecciation by carbonate undersaturated waters, "chalky" microporous thin beds, possible internal sediment	short-term subaerial exposure	"chalky" microporous thin beds cap HFC, most common in lower cycle in the Parks #118 core, oil-stained







Thin Section
Parks A#130
3203'
40X

Diagenetic facies that overprints all rock types

Porous or tight, depending on host rock type.

Porous zones are associated with shoals/flank deposits (sample on left), buildups (center) intermound (?, right)

Mudstones tend to be brecciated and interstitial pores are filled with internal sediment (samples on right)

Figure 14. Caddo, Facies 10: Altered, vaguely brecciated lime mudstone and wackestone (good reservoir).

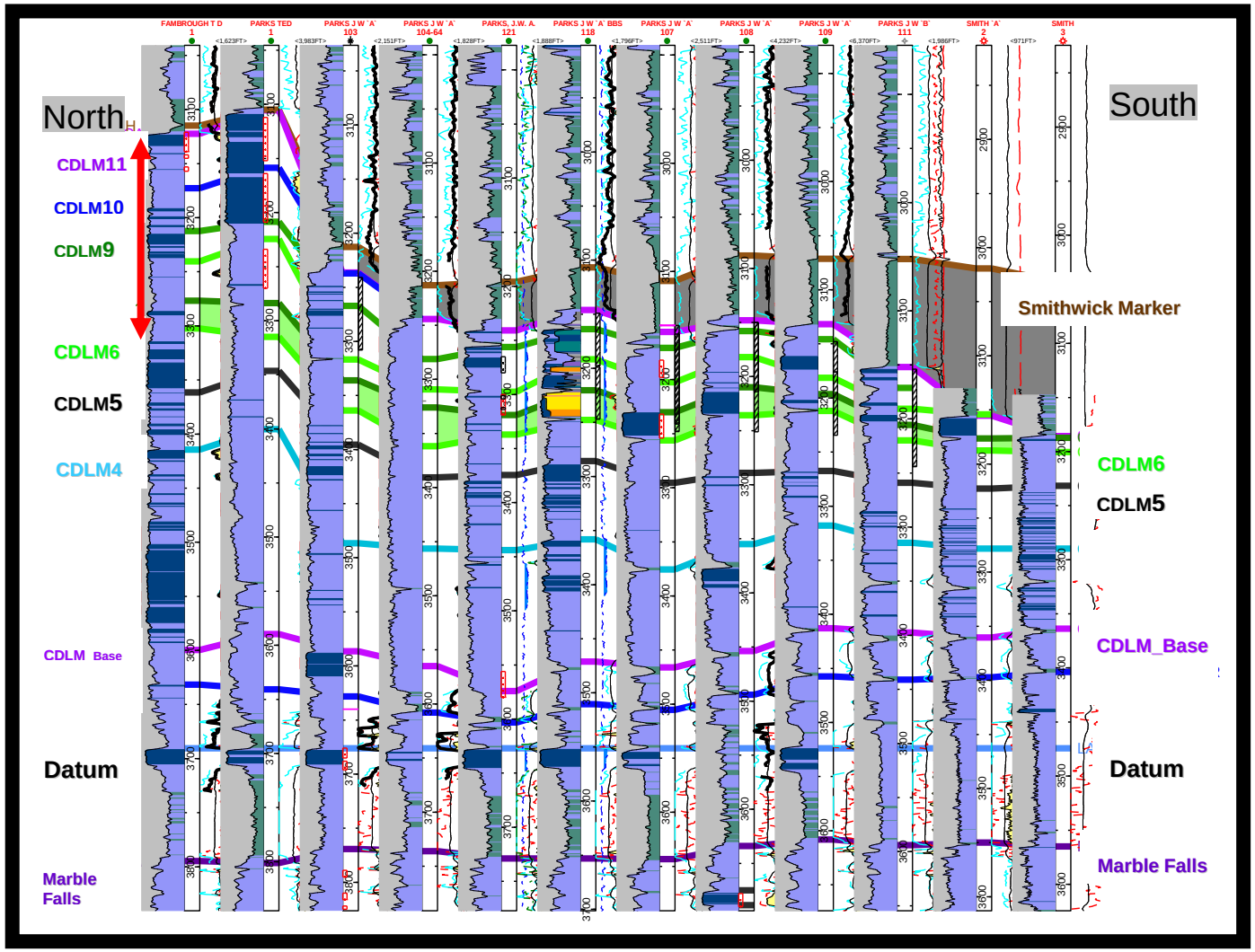


Figure 15. North-South cross section of the Gamma Ray illustrates the Caddo zones and thickening of the Caddo to the north and thinning to the south. The Caddo Lime (CDLM) flow units are labeled from CDLM 4-12 with the red arrow over the producing horizons CDLM 6-12. The Parks #118 in the center of this cross section represents one of the cored well that helped with the stratigraphic correlations. Figure 16A has the cross section located on the map. The capping Smithwick Shale thins as the carbonate thickens to the north.

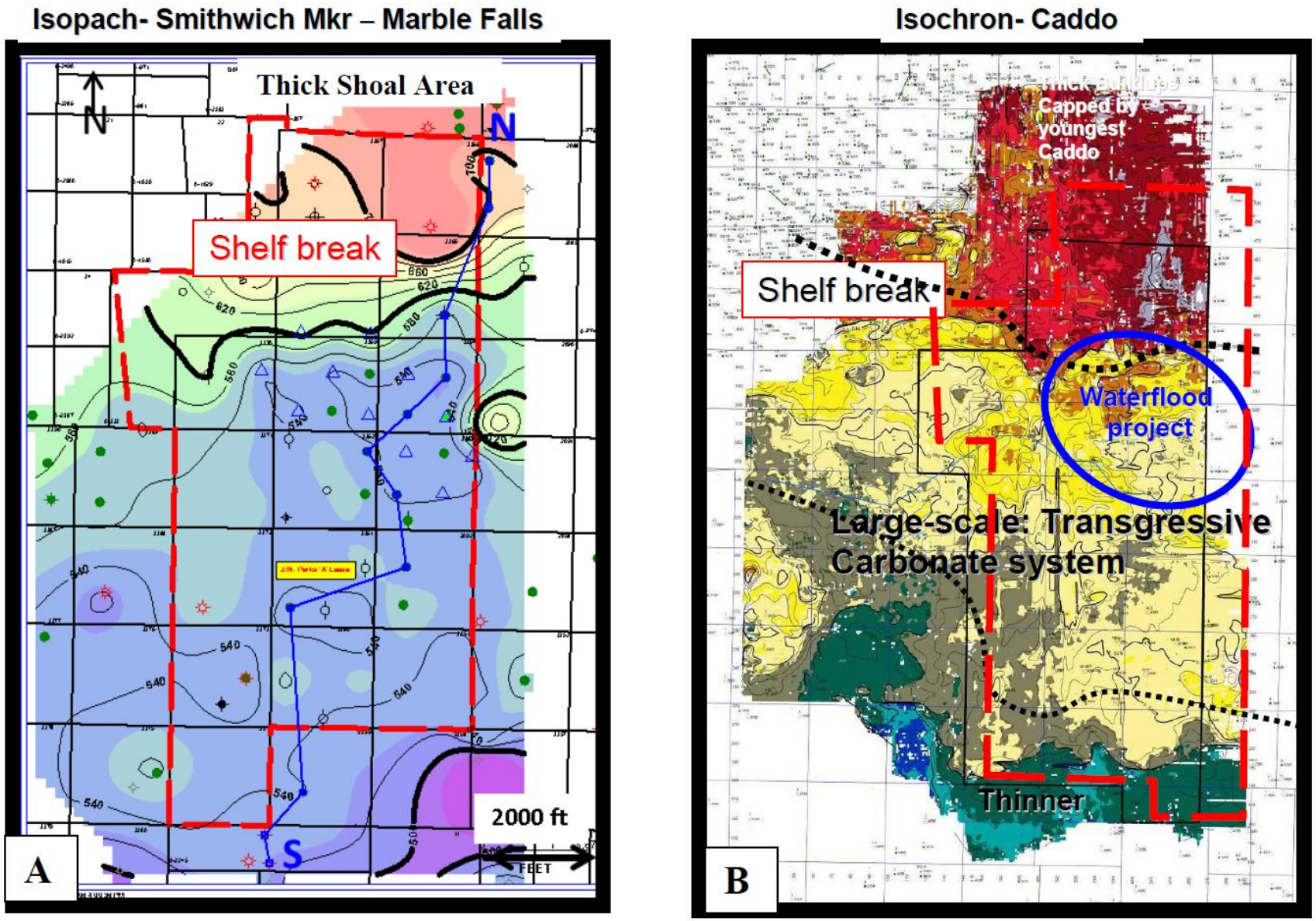
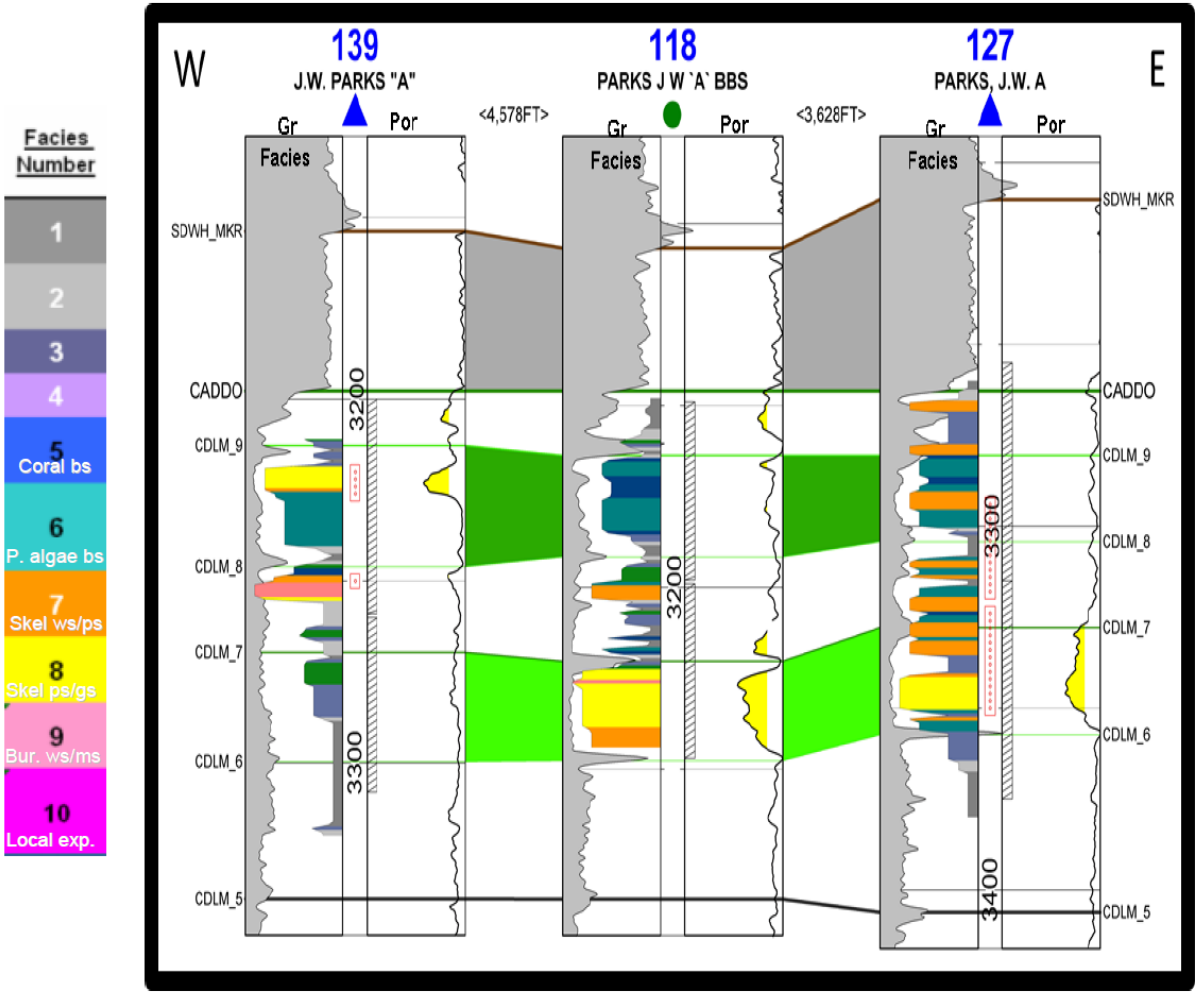


Figure 16. A. Isopach of the Smithwick to Marble Falls interval, illustrating the shelf break (where the contours are closely spaced). Hot colors are thicks (yellow-red) and cool colors are thins (blue-purple). Cross-section in Figure 15 is shown in blue.
B. Isochron from the 3D seismic survey over the area showing a similar relationship as the isopach. Hot colors are thicks (red) and cool colors are thins (blue). Shelf break could be edge zone of offshore, highly amalgamated buildups.



Mound core position is variable and generally reciprocal with grainy flank reservoir facies –

CDLM 9:

#139 Mound / Mound crest
#118 Mound (thick)
#127 Flank (thin)

CDLM 8:

#139 Distal Flank (thin)
#118 Mound / Mound crest
#127 Flank/Inter-mound

CDLM 7:

#139 Inter-mound
#118 Flank
#127 Distal Flank

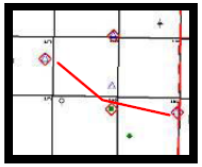


Figure 17. Mound vs. flank: Reciprocal relationships: General isopach trends -- Mounds = thicks; flanks/intermound = thins. Reservoir quality -- Mound = poor to fair; flank = good; intermound = fair.
Right-side of depth track is black hachured rectangle representing the cored interval, and the red rectangle on the left side of the track is the perforated interval. Parks #118 is still producing in the Duffer and has not been converted to a Caddo well.

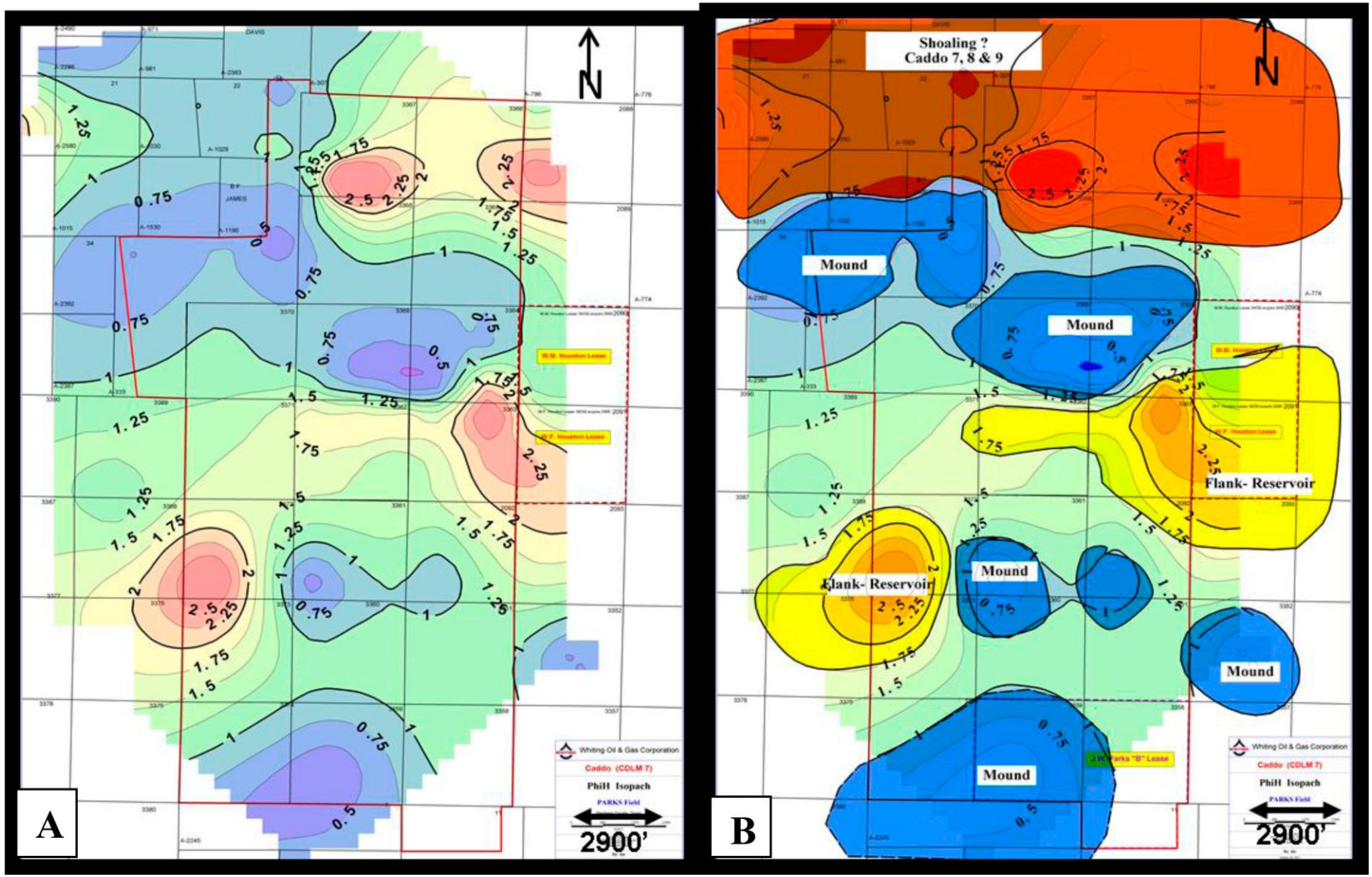


Figure 18. A. Pore Volume (PhiH) isochore (contours 0.25) of the Caddo 7 zone.
B. Interpreted facies based on core overlain on PhiH map with mound (blue); crest/flank (yellow) architecture with thickest reservoir on the mound flanks.

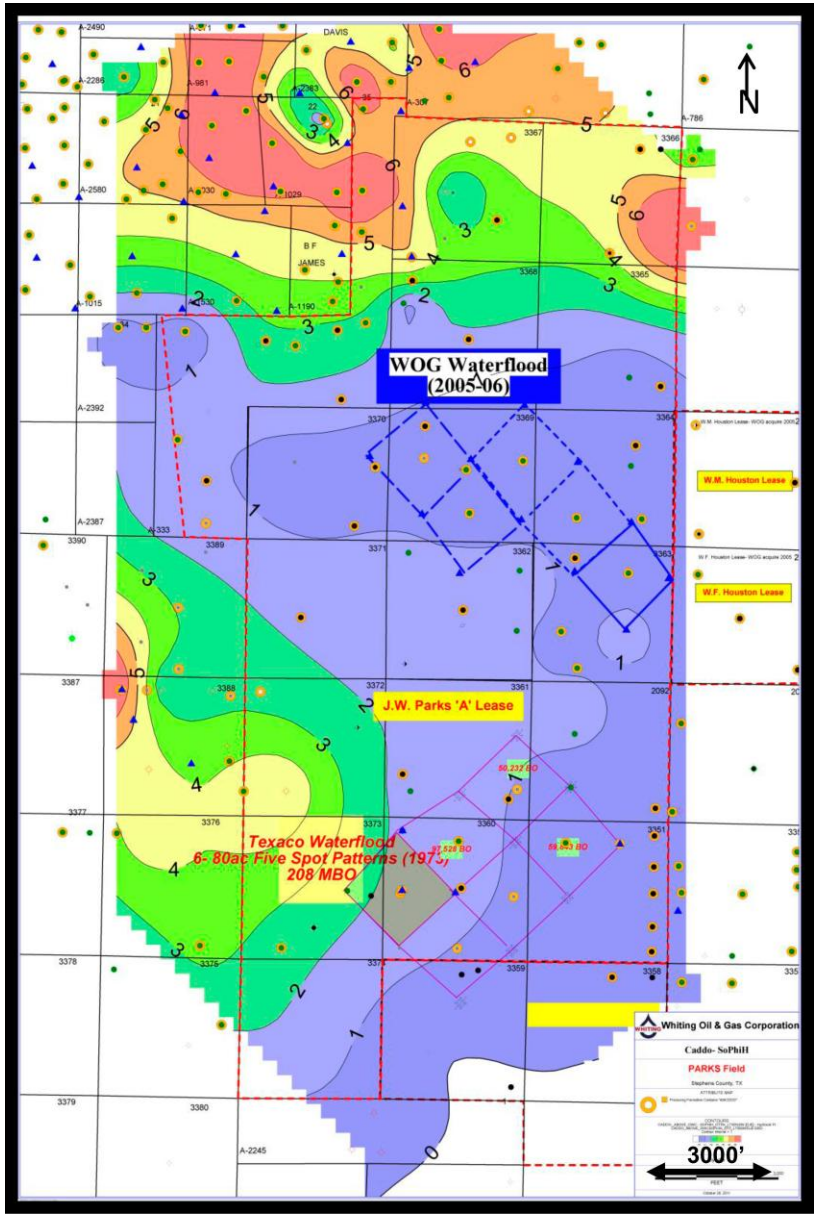


Figure 19. SoPhiH isochore map of the Caddo Lime (CI- 1). Short-dash blue line highlights the first two patterns put on injection with the solid blue line showing the strongest producing Pattern D. The Texaco waterflood is highlighted in purple patterns. Orange dots show wells that have produced from the Caddo.

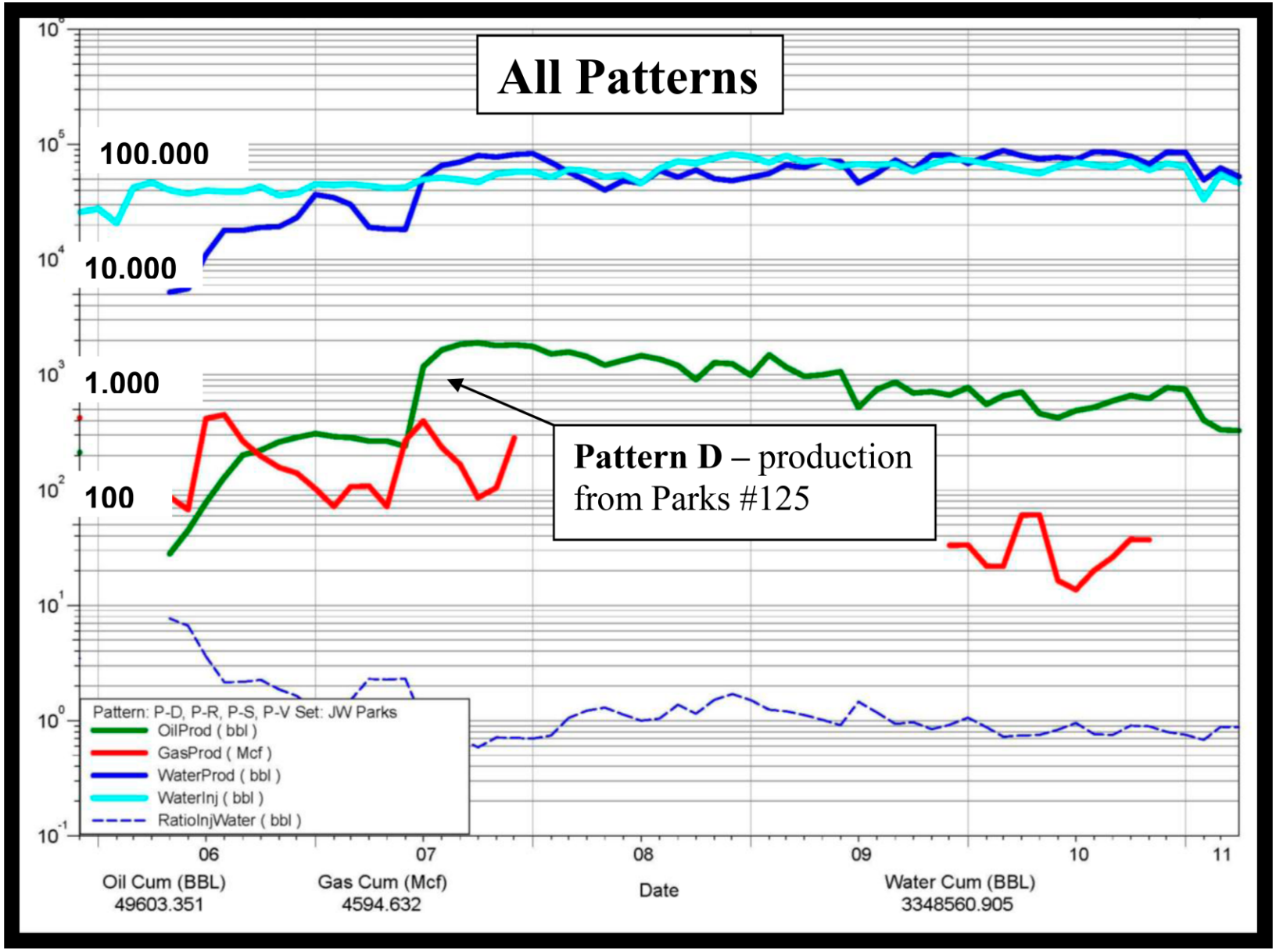


Figure 20. Production from all six waterflood patterns through October, 2010. There was a steady increase in production until 2007 at which time facilities were "maxed-out" and water was being diverted to Pattern D.