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Status Report

COMPARISON OF SHORELINE BARRIER ISLAND DEPOSITS FROM WYOMING, CALIFORNIA AND TEXAS

by
Viola Rawn-Schatzinger and Douglas Lawson

September 1994

Work Performed Under Contract No.
DE-AC22-94PC91008

Prepared for
Dr. Robert Lemmon, Program Manager
U.S. Department of Energy
Bartlesville Project Office

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Distribution Category UC-122

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ABSTRACT

This report fulfills the requirements of Task 1 Element 3, Work Package AC/15264/BC/42 revision B Reservoir Assessment and Characterization.

Wyoming produces oil from shoreline barrier deposits ranging in age from Cambrian to Cretaceous. These strandline/barriers were deposited along the shores of the Continental Sea and later preserved in six basins. California shoreline barrier formations are of early to Mid-Tertiary age and preserved in four distinct basins. These basins were separated by uplifted areas throughout the period of deposition. The shoreline barriers of Texas are represented by deposits of Cretaceous and Teretiary age and preserved in two adjoining basins.

The heterogeneous shoreline barrier island facies in Wyoming, California, and Texas are the same in all three settings, but differences in age of sediment, basin configuration, sediment input, and diagenesis reveal different aspects in the Class 4 deposits of Wyoming, California, and Texas. Because of the slow transgression of the Continental Sea, followed by massive post-depositional tectonic forces, sequences in the Paleozoic and Mesozoic rocks of Wyoming have shoreline barriers traceable in both outcrop and subsurface. In California the rapid sediment input, contemporaneous faulting, and movements caused by plate tectonics caused the formation of barrier islands which have depth but little lateral expression. In Texas the continual sediment input and low tidal energy caused the formation of thin, en echelon, elongate barrier islands which have undergone growth faulting but have not been subjected to tectonic movements which might have brought strandplain/barrier island formations to the surface.

In Wyoming the longer period of burial and influxes of fresh water following the initial saline water deposition and burial have caused complex diagenetic changes and extensive cementation. In California the tectonic uplifts, mountain building, and faulting were concurrent with deposition and continued after strandplain/barrier island deposition. The California deposits and the different fluctuations of water into the deposits have resulted in sediments which are often unconsolidated or poorly consolidated. The diagenetic effects on Texas shoreline barrier reservoirs is greater than those in California sediments, but somewhat less pronounced than those in Wyoming.

The average permeability and porosity of oil bearing rocks in Wyoming is much less than rocks in either California or Texas.

The Almond Formation in the Greater Green River Basin of Wyoming is an excellent site to continue research on the effects of sedimentary and diagenetic heterogeneity on recovery because of the close association of outcrops to similar facies in the subsurface.

EXECUTIVE SUMMARY

Reservoirs formed from coastal, strandplain/barrier island deposits have been placed into the fourth class of petroleum-producing sedimentary categories as determined by the Department of Energy (DOE). The Class 4 reservoirs listed in the DOE Tertiary Oil Recovery Information System (TORIS) database contain reserves of about 30.8 billion barrels of oil (MMMBO), which is about 9 % of the original oil in place (OOIP) for all of the United States. The current projected ultimate recovery from Class 4 reservoirs with the current technology is about 38% of OOIP, leaving about 19 MMMBO in place (NIPER/BDM 1994).

The reservoirs in California, Texas, and Wyoming contain about 85% of the Class 4 remaining oil in place (ROIP). About 85% of the current production is light oil with small independent oil companies producing 40% of this oil.

Coastal strandplain/barrier island deposits were laid down along a shoreline where wave and tidal forces dominated the movement of fluids and the sediment they transport. Tectonics and sediment supply rate control the thickness, lateral extent, and amalgamation of the strandplain/barrier island deposits formed. Whereas tectonics and sediment type affect reservoir quality, all of these factors contribute to the heterogeneity of the reservoir and the percent of oil that can be recovered with current technology.

The success of improved recovery methods in this class of reservoirs will depend heavily upon the effective characterization of the heterogeneous flow units within these complex reservoir formations. The methods of characterizing reservoirs derived from the studies of the Almond Formation must be applicable to other strandplain/barrier island reservoirs. Thus this comparative study of the relationship between reservoir characteristics and petroleum recovery was undertaken to help predict which methods of characterization will and will not be readily transferred to other Class 4 reservoirs. The study was undertaken to evaluate the suitability of other regions as potential sites for additional surface study.

The permeability and porosity are lower in the Wyoming reservoirs formed in strandplain/barrier island deposits primarily because of greater compaction, diagenetic cementation, and clastic sediment source than in California and Texas. This difference is reflected in the greater average depth of burial for the Wyoming reservoirs, including the Almond Formation. Useful characterization techniques can not neglect the differences in sediment source, diagenesis, and burial history from region to region or from surface to subsurface.

Postdepositional tectonic uplift in Wyoming has exposed at the surface strandplain/barrier island facies nearly identical to those producing petroleum in the subsurface. This is infrequently the case in Texas and almost never the case in California. This makes detailed studies of important characteristics of major reservoir facies at the surface possible almost exclusively in Wyoming.

ACKNOWLEDGMENTS

The authors wish to thank Arfon Jones, Min Tham, and Rick Schatzinger for their continued guidance throughout this project. The efforts of Maryann Greulich and Djaun Grissom helped to improve the manuscript. We wish to thank Madeline Reardon for editorial assistance. The support of Bob Lemmon, Project Manager, Bartlesville Project Office, U.S. Department of Energy is greatly appreciated. We appreciate the financial support of this research by the U.S. Department of Energy through a Management and Operating Contract DE-AC22-94PC91008.

1.0 INTRODUCTION

In order to appreciate the advantages of reservoir characterization and analysis of the Almond Formation in the Rock Springs Uplift (Wyoming) a survey of other regions with shoreline barrier islands was undertaken. Past work in the Reservoir Characterization Group has concentrated on barrier island facies and production from Bell Creek field (Montana) (Honarpour et al. 1989) and Patrick Draw field, Wyoming (Szpakiewicz et al. 1991; Schatzinger et al. 1992; Jackson et al. 1993). Outcrop comparisons of the Muddy Formation in northeast Wyoming and the Almond Formation in south central Wyoming have facilitated the analysis of the subsurface oil reservoirs in these regions. The major plays and petroleum providence in Wyoming, California, and Texas with Class 4 production were initially studied (NIPER/BDM-0027). The present study is a more detailed attempt to survey the stratigraphy and facies development of all the shoreline barriers of Wyoming, California, and Texas.

2.0 WYOMING

2.1 Introduction

Wyoming formed part of the western border of the Continental Sea, which covered the central part of the continent from Alaska to the Gulf Coast throughout the Paleozoic and Mesozoic eras. Deposition in what is now Wyoming was along the margins of the Western Interior Seaway portion of the Continental Sea. The effect of the seaway in this area was widespread, and several formations can be identified as marker beds across wide regions of the Rocky Mountains. Gradual subsidence of the Continental Sea coupled with episodes of uplift, tectonism and erosion form a complex stratigraphy which however, can still be correlated across basins. Figure 2–1 (Harrison 1980) is a stratigraphic correlation across Wyoming showing the interpretation of depositional units from basin to basin. One of the most visible and important boundaries to oil production is the Mowry Shale. The Mowry Shale represents a substantial regression of the Continental Sea covering most of Wyoming in the Early Cretaceous. It forms a boundary between lower Cretaceous and upper Cretaceous rocks and serves as a source for much of the lower Cretaceous petroleum reservoirs (Dolson et al. 1991; Berg et al. 1985).

2.2 Paleozoic Stratigraphy

2.2.1 Cambrian

2.2.1.1 Flathead Formation

The oldest Class 4 production from Wyoming Tertiary Oil Recovery Information System (TORIS) is from Lost Soldier field. The deepest reservoir at Lost Soldier produces from the Middle Cambrian Flathead Sandstone (Table 2–1). Most of the production at Lost Soldier field is from the Pennsylvanian Tensleep Formation (Kelly 1979; Smith 1980) with smaller reservoirs in the Mississippian Madison Formation and Darwin Member of the Amsden Formation (Harrison and Tilden 1988) and the Flathead Sandstone (Rickford and Finney 1989). Figure 2–1 (see Wind River Basin column) shows the stratigraphic relationship and lithology of these formations.

The Flathead Sandstone has a wide extent in the subsurface and has good surface exposures (Middleton et al. 1980). It was deposited in a trough from Western Montana, and southern Idaho through Wyoming to northeast Utah by the slowly eastwardly transgressing Continental Sea (Bell and Middleton 1978). The Flathead Sandstone, which forms the basal Paleozoic unit in this region (Fig. 2-1) has been described as a classic example of lower shoreface and nearshore subtidal environments (Keefer and Van Liew 1966; Maughan 1987). The Flathead Sandstone is the best Cambrian age reservoir in the Rocky Mountains (Bell and Middleton 1978).

Lost Soldier field pierces the Flathead Sandstone parallel to the Granite Mountains Uplift in northeastern Sweetwater County (Schmechel and McGuire 1986; Smith 1980). Class 4 production from shoreline barriers in the Flathead Sandstone is only a portion of the total production from Lost Soldier field.

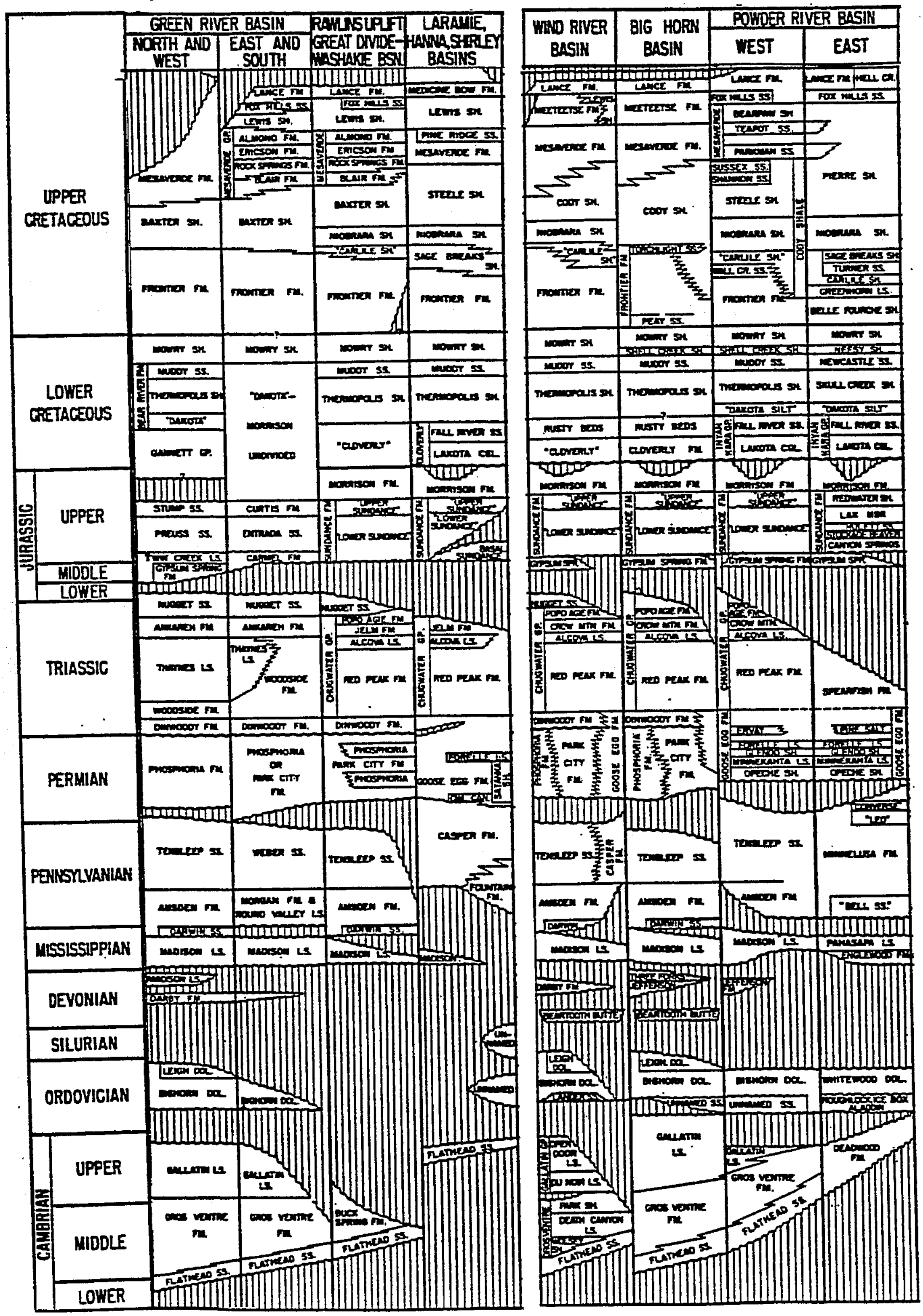

Figure 2–1 A stratigraphic nomenclature chart of Wyoming showing the basins and formations discussed. Modified from Harrison (1980).

Table 2–1 Class 4 Fields with ShorelineBarrier IslandDeposits in Wyoming with Production Statistics (TORIS).

Field Name	Reservoir	Formation	# Wells	Porosity %	Perm. mD	API	OOIP (bbl)	Depth ft	Net pay ft.
Chan	Muddy	Muddy Ss.	37	10	0.7	40	15,161,300	7035	9
Collums	Muddy	Muddy Ss.	6	14	2.3	40	23,562,800	7168	17
Dead Horse Creek	Parkman	Mesaverde	70	18	265	38	26,400,000	6924	44
Donkey Creek	Dakota	Dakota, Fall R.	18	16	75	38	11,348,800	6235	20
Fiddler Creek	Newcastle	Newcastle Ss.	36	24	30	40	55,661,600	5200	8
Gas Draw	Muddy	Muddy Ss.	16	20	188	35.7	50,503,410	7300	18
Gillette	Muddy	Muddy Ss.	20	10	0.7	43	1,773,250	8008	10
Grass Creek	Curtis	Cugwater	87	17	120	23.9	113,689,000	3500	20
Grass Creek	Darwin	Amsden	12	17	76	24	13,442,900	4400	29
Grieve	Muddy	Muddy Ss.	7	20	237	38	53,995,790	6650	41.1
Hilight	Minnelusa and	Muddy Ss.	236	22	173	41	479,258,100	10355	20
Kitty	Muddy	Muddy Ss.	332	13	200	42	98,332,710	9089	14
Lost Soldier	Flathead	Flathead	7	12	18	36	50,000,000	5145	94
Mill	Muddy	Muddy Ss.	20	14	5.6	39	9,830,930	8190	6
Miller Creek	Dakota	Dakota,Fall R.	26	18	200	32	17,000,000	5848	26
Patrick Draw Arch	Almond	Almond Ss.	42	19.7	36	42	104,860,000	5200	20
Patrick Draw Monell	Almond	Almond Ss.	41	20.9	36	42	89,332,590	5400	20
Poison Spider	Mesaverde	Mesaverde	16	16	63	43	19,984,590	9230	30
Recluse	Muddy	Muddy Ss.	52	16	300	40	57,322,800	7599	25
Rock River	Cretaceous	Muddy, Dakota	54	17	20	36	60,591,100	2750	69
Rozet	Muddy	Muddy Ss.	47	20	52	36	71,218,400	7000	18
Sandbar, East	Muddy	Muddy Ss.	6	16	11.7	42	20,988,000	6766	12
South Glenrock	Upp. Muddy	Muddy Ss.	52	20.1	240	37.5	37,034,800	6290	8
Springen Ranch	Muddy	Muddy Ss.	14	20	26.3	40	45,525,500	7487	15
Ute	Muddy	Muddy Ss.	28	17	16.8	38	43,991,500	6404	10
Wertz	Darwin	Amsden	3	14	128	36	13,000,000	6447	30
Whitetail	Muddy	Muddy Ss.	12	20	47.6	35	13,618,600	6757	8
AVERAGE				17.1	95.137			6606.6	23.744
Standard Deviation				3.5238	94.335			1669.1	19.565

2.2.2 Mississippian-Pennsylvanian

2.2.2.1 Amsden Formation

Two fields in the southern Bighorn Basin of Wyoming produce oil from Class 4 shoreline barriers from upper Paleozoic and lower Mesozoic rocks (Table 2–1). Wertz and Grass Creek fields have deep production from the Darwin Member of the Amsden Formation (see Fig. 2–1) (Cardinal 1989). The Darwin Sandstone is the basal member of the Amsden Formation and it straddles the Mississippian-Pennsylvanian boundary (Maughan 1987). The Darwin is a fine- to medium-grained sandstone deposited as eolian dunes in a subkha environment (Maughan 1987).

2.3 Mesozoic Stratigraphy

2.3.1 Triassic

2.3.1.1 Chugwater Formation

Grass Creek field also has several producing horizons above the Darwin Sandstone (Smith and Surdam 1992; Cardinal 1989) including Class 4 production from the Curtis Member of the lower Triassic Chugwater Formation. Rocks of the Chugwater Formation and Group are found from the Denver Basin north and west in Wyoming to the Wind River and Bighorn Basins, but it is not correlated in the Green River and Washakie Basins, (Figs. 2–1 and 2–2). Although the Chugwater Formation is widespread and has varying facies and lithologies, Grass Creek is the only field where Class 4 deposits have been identified. Figure 2–2 shows the relationship of basins and uplifts in Wyoming and demonstrates the pattern of interconnectedness of the basins.

2.3.2 Cretaceous

2.3.2.1 Introduction

Although four fields produce from stratigraphic reservoirs of Paleozoic and Early Mesozoic ages by far the greatest production from Class 4 reservoirs in Wyoming is from Cretaceous age rocks. Essentially there are two areas of Cretaceous age Class 4 reservoirs in Wyoming, the Greater Green River and Powder River basins (Fig. 2–2).

Shoreline barrier island production in the Power River Basin is primarily from the Muddy Formation and equivalent age lower Cretaceous rocks (Fig. 2–1). In the Greater Green River Basin shoreline barrier production is from rocks of the Mesaverde Group, principally the Almond Formation.

Literature on the lower Cretaceous Muddy and the upper Cretaceous Almond formations is extensive (Rawn-Schatzinger and Schatzinger 1993). Oil exploration in the Powder River Basin began around World War I (Merschant 1985), but increased greatly in the 1960s–80s (Cardinal 1989). Production from Almond reservoirs in the Rock Springs Uplift began at Patrick Draw in 1959 and increased through the 1960–1980s (Keighin et al. 1989; Richers 1990).

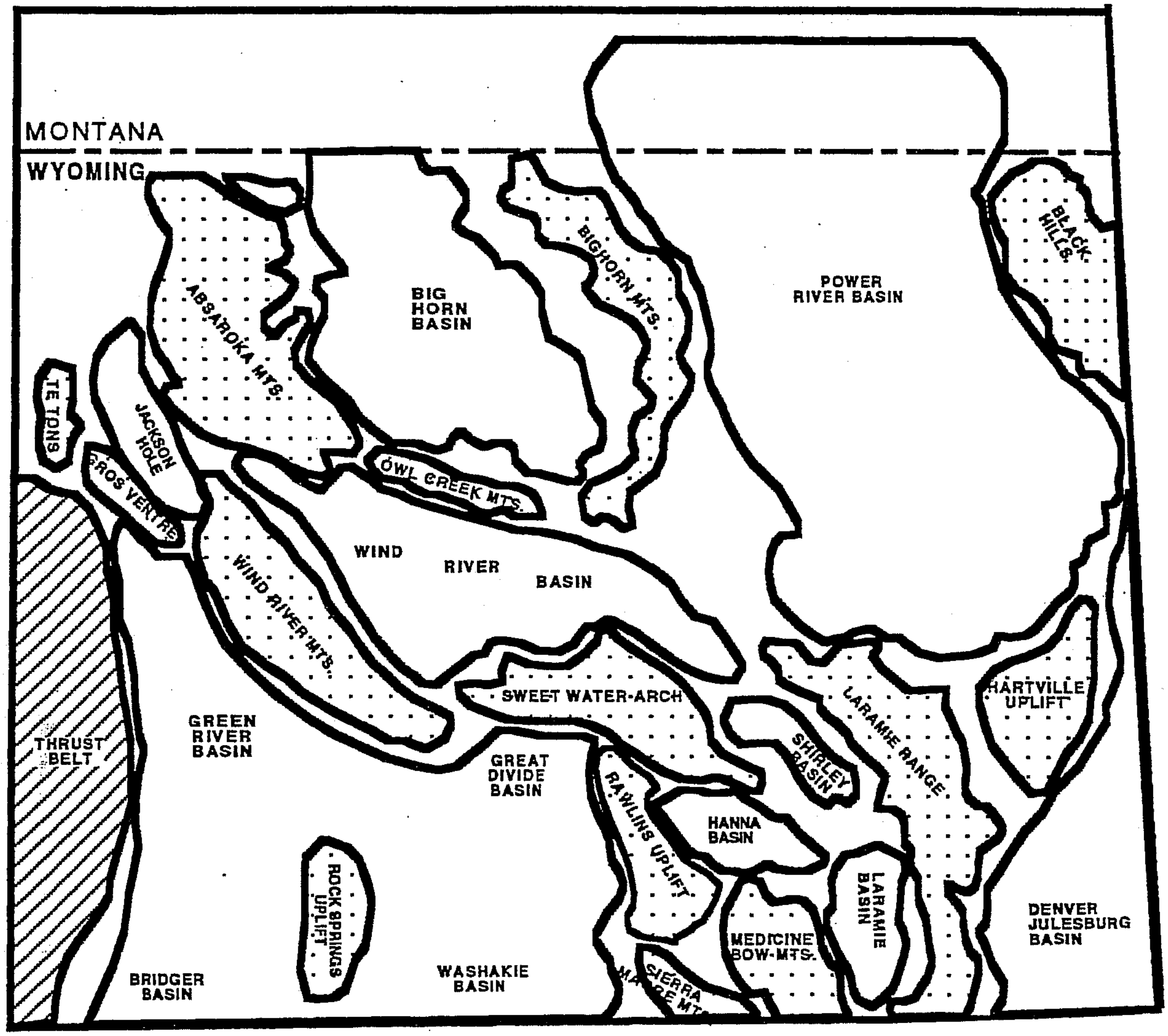

Figure 2–2 A structural index map of Wyoming showing basins and uplifts. Dotted area indicates mountains and uplifts, lined area indicates Wyoming Folded Thrust Belt. Based on Hausel (1980).

Cretaceous age fields producing from Class 4 shoreline barrier island deposits in the Powder River Basin include (Table 2–1); Chan, Collums, Gas Draw, Gillette, Grieve, Hilight, Kitty, Fiddler Creek, Mill, Recluse, Rock River, Rozet, Sandbar-east, South Glenrock, Springen Ranch, Ute, and Whitetail. These all produce from reservoirs in the Muddy Formation or equivalent rocks.

2.3.2.2 Fall River Formation

The lowest unit in the Powder River Basin producing from a Class 4 reservoir is the Fall River Formation Member of the Dakota Group at Donkey Creek, Miller Creek, and Rock River fields (Table 2–1). The Fall River is a lower Cretaceous sequence of sandstones and shales below the Skull Creek Shale (Fig. 2–1). Outcrops of the Fall River are recognized some distance east in the Black Hills Uplift (Rasmussen et al. 1985). Economically the oil reservoirs of the Fall River Formation are very significant, but reservoirs at Donkey Creek, Miller Creek, and Rock River are the only fields where the deposition of environment can be defined as shoreline barrier island (TORIS). In other fields and outcrops the Fall River is defined as deltaic (Rasmussen et al. 1985).

2.3.2.3 Newcastle Formation

Fiddler Creek produces from a reservoir in the Newcastle Sandstone, which is age equivalent to the Upper Muddy (Fig. 2–2.). The Newscastle Sandstone is found in subsurface and outcrop in the eastern part of the Powder River Basin and outcrops further east in the Black Hills (Rasmussen et al. 1985).

2.3.2.4 Muddy Formation

The shoreline barriers of the Muddy Formation are extensive in the Powder River Basin. Figure 2–3 shows the major fields in the Powder River Basin in Wyoming and Montana (Berg 1976a). Except for Clareton all the fields shown have some production from shoreline barrier island deposits (Table 2–1).

Bell Creek field in Montana has produced from a series of six separate barrier bar sandstone reservoirs in the lower Cretaceous Muddy Formation (Honarpour et al. 1989). These reservoirs have been the subject of waterflooding and two EOR projects designed to increase recovery efficiency (Honarpour et al. 1989). Reservoir studies (Honarpour et al. 1989) at Bell Creek field found that production from the Muddy reservoirs was controlled by five geological factors: (1) stratigraphic relation of barrier sandstones to valley fill deposits; (2) development of the barrier island facies, including the internal distribution of facies and the stacking or overlap of subsequent cycles or barrier deposition; (3) depth and width of erosional cuts into the top of barrier island and the type of the infilling, (4) distribution, type, and degree of diagenesis (clay filling, compaction, cementation), (5) local faulting which appears to modify fluid flow patterns between wells.

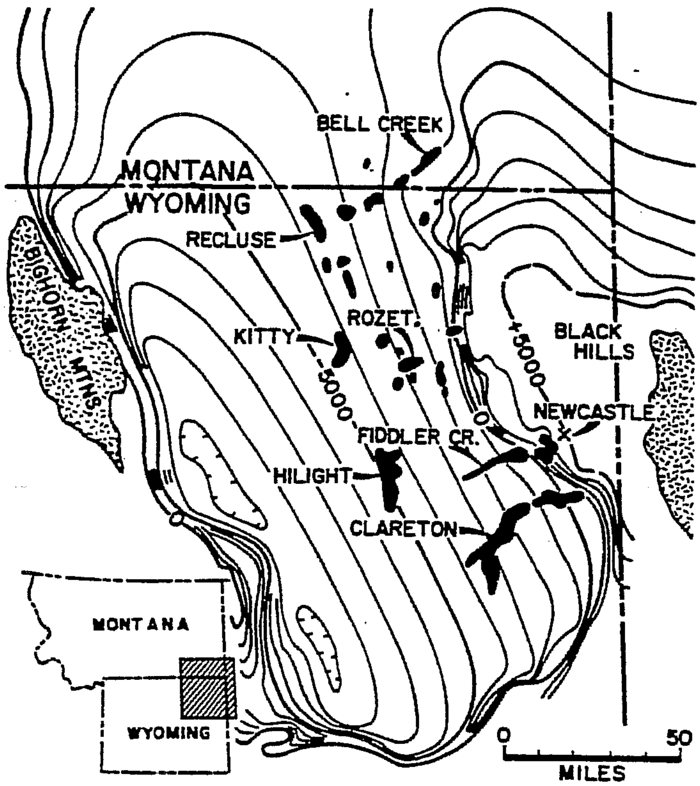

Figure 2–3 Powder River Basin showing structure on top of the Lower Cretaceous Fall River (Dakota Group) Sandstone and locations of major oil fields producing from the Fall River and Muddy Formations (Berg 1976a).

The geological model developed at Bell Creek field, which may be applied to other fields producing from both the Muddy Formation and other shoreline barrier island deposits demonstrates that superior reservoir quality is found in foreshore, upper and middle shoreface, and washover facies; while poorer reservoir quality comes from associated valley cut and fill facies (Honarpour et al. 1989).

Within the Powder River Basin, the Muddy Sandstone is described as a sequence of thin sandstone units with low permeability, but effective porosity (see Table 2–1) (Berg 1976b; Larberg 1980). Individual sandstone units vary from less than 10–20 ft thick (Berg 1976; Larberg 1980). At Grieve field the pattern described from Bell Creek field is seen in lower paleovalley fills, covered by marine sands and muds deposited during a transgression (Curry 1985).

The Muddy Formation is divided lithologically into two units. The Lower Muddy was deposited as point-bar sands within stream channels cut into the underlying Skull Creek Shale, and the Upper Muddy was deposited as barrier bars in near-shore and off-shore marine waters (Merschant 1985). Kitty field has reservoirs in both the Upper and Lower Muddy, while Springer Ranch, Gas Draw, Bell Creek, and Collum fields have reservoirs in the Upper Muddy. Reservoirs at Recluse field are in the Lower Muddy (Larberg 1980).

Discovery of Recluse field, extensions of Kitty and Bell Creek fields in 1967 and discovery of Sandbar, Whitetail and Gas Draw fields in 1968 demonstrated the importance of oil reserves in shallow marine barrier island deposits (Womcik 1972). Much of the production from the shoreline barrier deposits in the Powder River Basin is attributed to stratigraphic traps along the flanks of the Big Muddy anticline (Curry and Curry 1972; Berg 1976a; Merschant 1985).

By 1991 reservoirs in the Muddy Sandstone had produced over 1.5 billion bbl oil (Dolson et al. 1991). In the transgressive sequences of the Muddy, control of production is by unconformities formed during relative sea level lowstands (Dolson et al. 1991). Within sandstone units fluid flow patterns are controlled by the distribution of pores and a reflection of thickness of a particular lens shaped sand body (Berg et al. 1985). Hydrocarbon source rocks are recognized in both the underlying Skull Creek and Mowry Shales (Dolson et al. 1991; Berg et al. 1985).

2.3.2.5 Mesaverde Formation

Dead Horse field in the Powder River Basin produces oil from a Class 4 reservoir in the Parkman Member of the Mesaverde Formation (Table 2–1). The Parkman Sandstone is the lowest member of the Mesaverde Formation present in the Powder River Basin and is roughly equivalent to the Rock Springs Formation of mid-upper Cretaceous age in the Green River Basin (Fig. 2–1).

Figure 2–4, (Szpakiewicz et al. 1991) is an idealized section of the Continental Sea coast showing the major shoreline barrier island facies and marking representative positions of fields in the Powder River and Green River Basins. It illustrates that all the facies of shoreline barriers are not present in one location. Preservation of these facies may further reduce the deposits present in any particular field. No distances or lateral relationships of fields are implied in the sketch.

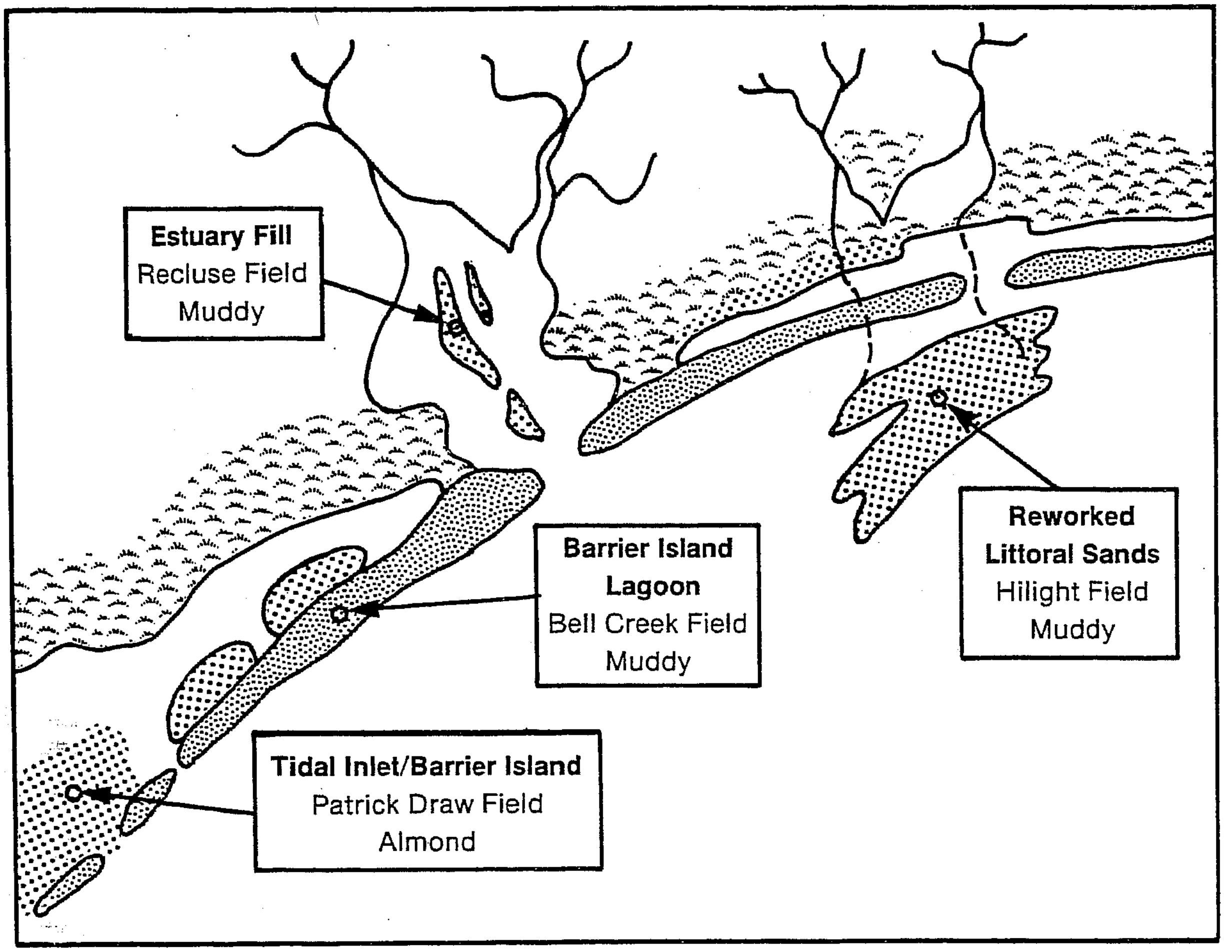

Figure 2-4 Diagrammatic map showing relative locations of ancient oil productive shoreline barrier sandstones in Wyoming and Montana. Not to scale (Szpakiewicz et al. 1991; Berg 1986).

Cretaceous age Class 4 fields reported by TORIS from the Greater Green River Basin (Table 2–1) are Poison Spider from undifferentiated Upper Mesaverde Group sandstones in the Hanna Basin, and Patrick Draw Arch, and Patrick Draw Monell Unit from the Almond Formation in the Washakie Basin. Stratigraphically the Upper Measverde Group at Poison Spider and the Almond Formation are age equivalent (see Fig. 2–1). Martinsen, Martinsen, and Steidtmann (1993) use the term *allostratigraphic* to describe the complex stratigraphic relationships of the Mesaverde Group in the Greater Green River Basin.

Poison Spider field is located in the Hanna Basin in south central Wyoming. Although Hanna Basin is the deepest basin in the Rocky Mountains, the depositional sequences left by transgressions of the Continental Sea can be clearly correlated with those in the Green River Basin (Martinsen, Martinsen, and Steidtmann 1993). The shoreline of the Continental Sea at the time of deposition in Hanna Basin was 50–100 km west near Rock Springs and oriented north south (Lillegraven and Ostresh 1990). An increasing sand supply on the surface of the Steele Shale formed offshore sand ridges, while coastal progradation in the eastern Hanna Basin formed the fluviodeltaic deposits of the Allen Ridge Formation, and shoreface and marine sediments in the Hanna and Laramie Basins (Martinsen, Martinsen, and Steidtmann 1993).

2.3.2.6 Almond Formation

In the Washakie Basin and Rock Springs Uplift part of the Greater Green River Basin 33 fields (Table 2–2) produce oil from Almond Formation reservoirs (Martinsen and Christensen 1992). Except for the Arch and Monell units at Patrick Draw field cumulative production (Table 2–2) from these fields has been too low for inclusion in the TORIS database. However, these fields demonstrate how widespread the Almond Formation and its shoreline barrier island deposits are. Figure 2–5, the paleogeographic setting of the Almond Formation, shows the position of the Rock Springs Embayment and the Continental Sea in the upper Cretaceous. The Muddy Formation at Bell Creek field (Montana) formed off the Sheridan Delta in the lower Cretaceous.

The Upper Eriscon, Almond, and Lewis Shale formations mark the final transgression the Cretaceous Seaway (Continental Sea) in southwestern Wyoming (Van Horn 1979). They were deposited along the meso-tidal barrier island coastline (Fig. 2–5) in fluvial-coastal plain, estuarine, and open-marine littoral and shallow neritic environments (Van Horn 1979). The mappable area of the Almond Formation barrier is over 60 miles long and 4 miles wide (Roehler 1988) with 18 miles of outcrops on the east flank of the Rock Springs Uplift (Fig. 2–6). The outline of the Almond Formation outcrops around the Rock Springs Uplift reflects the broad basinal distribution of the Almond in subsurface. The location of Patrick Draw field in the Washakie Basin is 20 miles east of the Almond outcrops (Roehler 1988).

Table 2–2 Oil Fields in the Rock Springs Uplift which Produce from the Almond Formation (Wyoming Oil and Gas Conservation Commission, 1992; Martensen and Christensen, 1992).

Field	Producing Form.	Por.	Perm, mD	API°	1991 Oil Prod. bbls	1992 Oil Prod. bbls	1991 Gas Prod. Mcf	1992 Gas Prod. Mcf	NetPay ft	Depth ft	Wells
Antelope	Almond	15%	5.00	60°	18,202,647	133	22,889	586,564	25	6,233	6
Baggs, South	Almond	20%	0.20		9,753		4,052,410		22	6,150	
Barrel Springs	Almond	11%	0.10	57°		668		38,757	110	8,402	2
Bitter Creek	Almond	10%	1.00	62°		37	60,304	36,332	31	11,000	3
Canyon Creek	Almond	12%	0.10	65°		14,372	8,281,273	3,070,476	25	4,800	36
Daeaney Rim Un	Almond	15%	2.60	52°		28,462	183,350	337,993	14	8,960	9
Desert Flats	Almond	14%			2,056		49,720		25	9,730	
Desert Springs	Almond	18%	10.00	58°	742,466	28,462	14,666,046	337,993	10	3,810	32
Desert Springs, W.	Almond	16%	11.40	43°	583,148		98,529,195		18	5,900	
Echo Springs	Almond	14%		62°	27,929	60,401	1,227,430	3,074,627	30	9,450	24
Hallville	Almond	22%			29,815	205	2,737	0	5	1,300	2
Hansen Draw	Almond	13%							10	11,800	
Haystack	Almond	13%							70	15,500	
Higgins	Almond	16%	24.00		4,113	192	3,479	1,829,882	24	6,715	8
Kinney	Almond	15%	15.00		16,094	601	14,151,201	693,886	16	4,750	8
Neff	Almond	10%			25		32,795		13	6,180	
Patrick Draw, Arch	Almond	20%	36.00	45°	17,257,130	40,051	35,220,576	891,521	20	5,066	15
Patrick Draw, No.	Almond	17%	22.45	41°	1,646,980	108,233	2,560,176	3,175,687	12	5,300	43
Patrick Draw, Monell	Almond	20%	35.92	45°	35,540,549		100,150,000		20	5,180	
Red Desert	Almond	12%	0.50	48°		939		43,529	25	9,695	4
Roser	Almond	15%							27	3,320	
Sand Butte	Almond	20%	14.00			0	1,735,221	105,640	14	4,800	3
Sheep Camp	Almond	13%			1,572	5,110	3,946	42,635	200	8,300	2
Siberia Ridge	Almond	8%	0.17	50°	2,841	13,221	796,721	1,567,273	6	6,500	32
Stage Stop	Almond	22%	29.00	44°		17,929	6,500	224,071		6,634	10
Table Rock	Almond	17%	2.30	40°	1,383,367	195,418	124,367,088	15,794,251	60	6,300	100
Ten Mile Draw	Almond	23%	20.00	64°		292	812,286	477,886	5	4,230	5
Wamsutter	Almond	13%	0.30		396,785	43,522	33,306,003	4,798,020	20	9,600	41
Robin	Almond, Lower	20%		39°		0		24,385	35	7,100	1
Robin	Almond, Upper	19%		39°	124,824		283,393		26	6,600	1
Tierney, North	Almond / Allen Rid.	12%		54°		15,361	428,857	597,821	15	10,060	11
Wild Rose	Almond / Allen Rid.	12%		48°		22,628	1,288,424	1,120,924	20	9,800	32
Creston 111 Un	Almond / Ericson	14%		60°	133		90,216		25	8,410	
Middle Mountain	Almond / Ericson	15%	0.70		56,052	0	8,857,777	5,716	25	6,450	1
Robbers Gulch	Almond / Ericson			60°			2,792		25	6,900	
Salazar	Almond / Ericson	10%					128,516		65	12,700	
AVERAGE		15%	10.99						31.229	7,323	
STANDARD DEVIATION		4%	12.37						35.98	2,866	

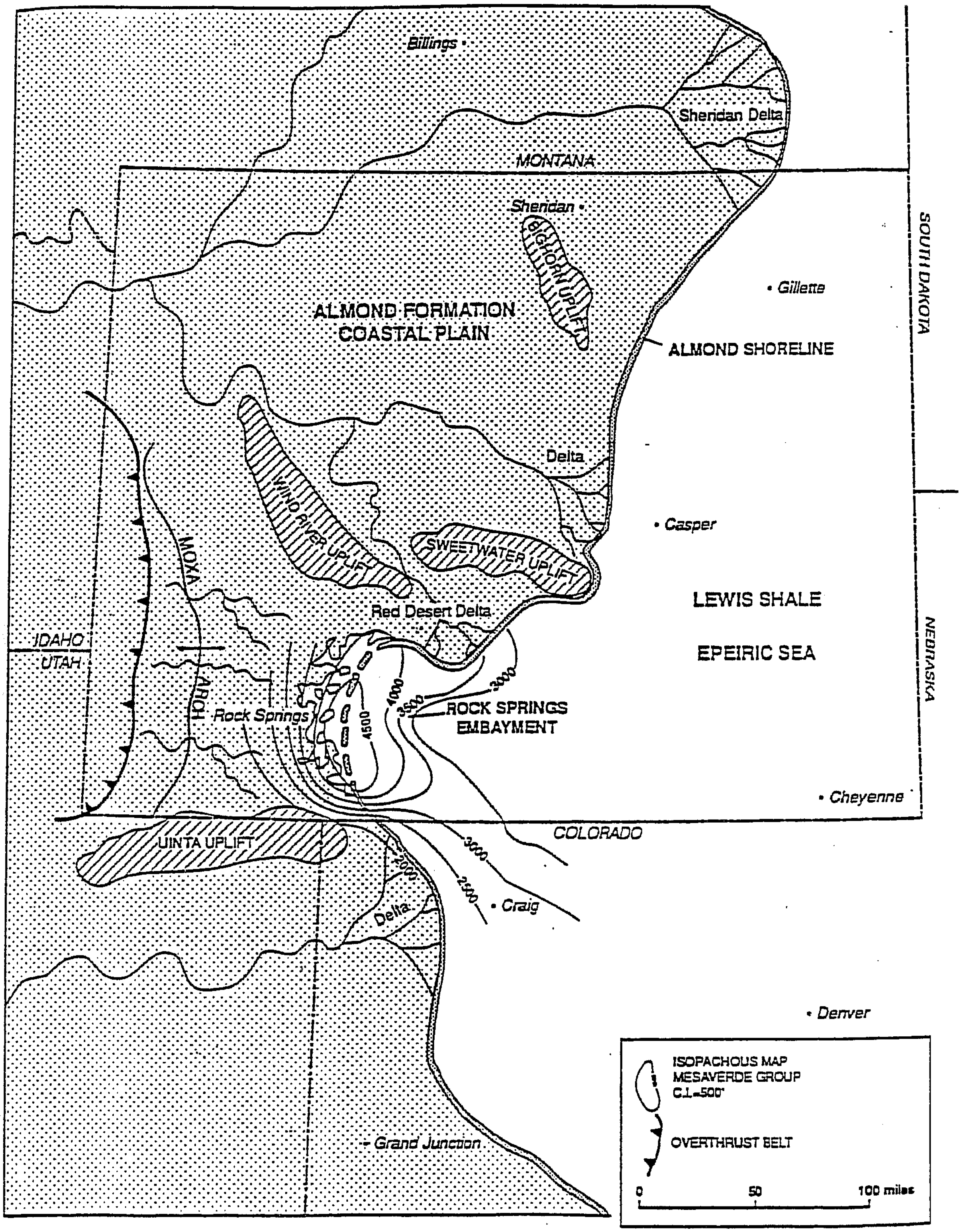

Figure 2–5 Paleographic setting of the Almond Formation in southwestern Wyoming. Eperiric Sea is the Cretaceous sea (Martinsen and Christensen 1992). Modified from Roehler (1988) and (1990).

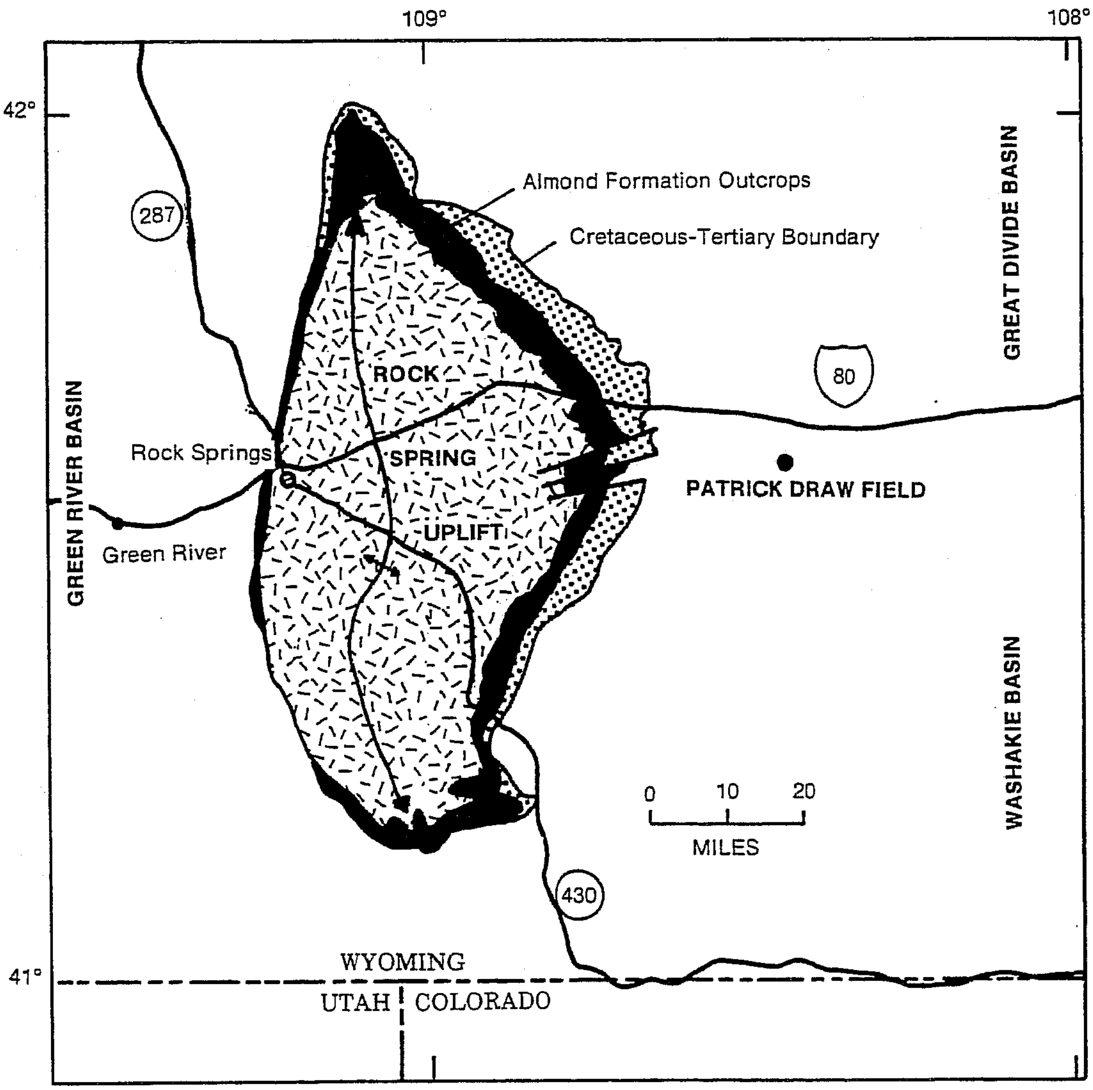

Figure 2–6 Rock Springs Uplift showing Almond Formation outcrops and location of Patrick Draw field. Modified from Roehler (1988).

The Almond Formation is divided into two units, upper and lower. The Lower Almond lies conformably over the Canyon Creek Sandstone, and has fluvial dominated deposits and fresh water marsh and swampy coal beds (Van Horn 1979). The Upper Almond unconformably overlies the Lower Almond and is represented by units of very fine- to medium-grained sandstones (Van Horn 1979)

Schatzinger et al. (1992) described the major depositional features of the Almond Formation within the Arch Unit at Patrick Draw field: (1) thin sand areas containing low-permeability sediments of oyster coquina, carbonaceous shale, and shaley sand formed either in a lagoonal setting or as an abandoned channel fill deposit, (2) thick sand areas of tidal channel overlain by tidal delta deposits, that contain the best reservoir quality rocks, (3) impermeable rock units with limited lateral extent (10s to 1,000s ft), (4) coal beds prone to parting and fracturing during fluid injection, (5) calcite-cemented oyster shell zones that are barriers to vertical flow. Tidal inlet, tidal channel, and tidal delta facies have the highest permeabilities (mean 20 mD) and mean porosities of 20% (Schatzinger et al. 1992).

Large scale features such as fracture and fault systems have a significant effect on fluid distribution and movement with in reservoirs at Patrick Draw field (Jackson et al. 1993). Faults bounding the highly productive thick sands that straddle the Arch-Monell Unit boundary provide an indication that some synsedimentary structural control of sand accumulation probably exists (Jackson et al. 1993).

Three lines of evidence suggest lateral compartmentalization at Patrick Draw field: (1) production of oil only from the updip portion of the reservoir, (2) a precipitous drop in formation water salinity downdip in the deeper parts of the reservoir, and (3) a marked decrease in formation pressure during primary production in the downdip portion of the reservoir (Schatzinger et al. 1992). Carbonate-cemented areas associated with the barrier to flow may have formed relatively early and remained topographically high during deposition of higher sand bodies in the Almond Formation (Jackson et al. 1993).

Vertical distribution of facies within cored wells indicates that successively offlapping thin sand wedges migrated seaward forming barrier systems with little lateral migration of inlet/tidal delta complex (Jackson et al. 1993). The Almond Formation, particularly the Upper Almond, is the main reservoir of the Mesaverde Group for the Greater Green River Basin (Martinsen and Christensen 1992).

3.0 CALIFORNIA

3.1 Introduction

Oil production from shoreline barrier island deposits in California comes from Tertiary sediments in four major basins in southern California: Cuyama Basin, San Joaquin Basin, Salinas Basin and the Santa Maria Basin (Fig. 3–1), deposits range in age from Eocene to Pliocene, but are predominately Miocene in age. The stratigraphy of the southern California basins is very complex because of the tectonic movements. The full development of marginal transform and strike-slip faults in the Neogene resulted in a productive petroleum province in central California; discrete moderate-sized, structurally controlled sedimentary basins, deposited during a period of rapid subsidence, and filled with organic rich sediments (Graham 1981). The basins are separated by (1) major faults: San Andreas, Garlock, White Wolf, Russell, and Rinconada; (2) Mountain ranges: Santa Monica Mountains, San Rafael Mountains, La Panza Range, Caliente Range, and San Emidio Range; and (3) major uplifts: Bakersfield Arch and Stockton Arch. Figure 3–1 shows the position of the southern California oil producing basins with major shoreline barrier deposits. Figure 3–1 also shows the relationship of arches, major faults and ranges along the Great Valley of California. The southern part of the San Joaquin Valley between the Bakersfield Arch and the White Wolf fault is sometimes referred to as the Maricopa Basin or subbasin (Bazeley 1972). These Early Tertiary basins in south and central California resulted from right-lateral slip along a proto-San Andreas fault (Nilsen and Clarke 1975). The basins formed by crustal stretching and extension and represent grabens bounded by normal faults at high angles to the major transform fault zone (Nilsen and Clark 1975).

While extensive production occurs in the southern San Joaquin, Salinas, Cuyama, and Santa Maria Basins, exploration in the late 1980s centered on the Sacramento Basin north of the San Joaquin Basin in the Great Valley (Thurston, Mason and James 1987). No Class 4 production has been reported from the Sacramento Basin (TORIS). Table 3–1 based on the TORIS database shows all California fields with oil production reported from Class 4 reservoirs.

3.2 Cenozoic Stratigraphy

3.2.1 Eocene

3.2.1.1 Llajas Formation

The oldest sediments from California attributed to shoreline barrier island deposition are from the Llajas Formation (TORIS). Sheills Canyon field has produced oil from 32 wells drilled in the Eocene age Llajas Formation (Table 3–1). The Llajas is a 1200-ft-thick deposit of interbedded fine-grained sandstone and siltstone, locally fossiliferous, with thin discontinuous beds of very coarse-grained sandstone and cobble conglomerate (Nilsen and Clarke 1975). Shiells Canyon field is at the base of the Santa Monica Mountains west of the San Andreas fault (Nilsen and Clarke 1975). The Llajas Formation has been interpreted as shallow marine in origin (Yerkes et al. 1971; Campbell et al. 1970; Nilsen and Clarke 1975). The TORIS data base attributes some of the production to Class 4 reservoirs (Table 3–1). However, it is impossible to determine the extent of shoreline barrier production from the Llajas Formation because the information in the database apparently combines production from the entire 1200-ft thickness of the formation, not specific depositional units.

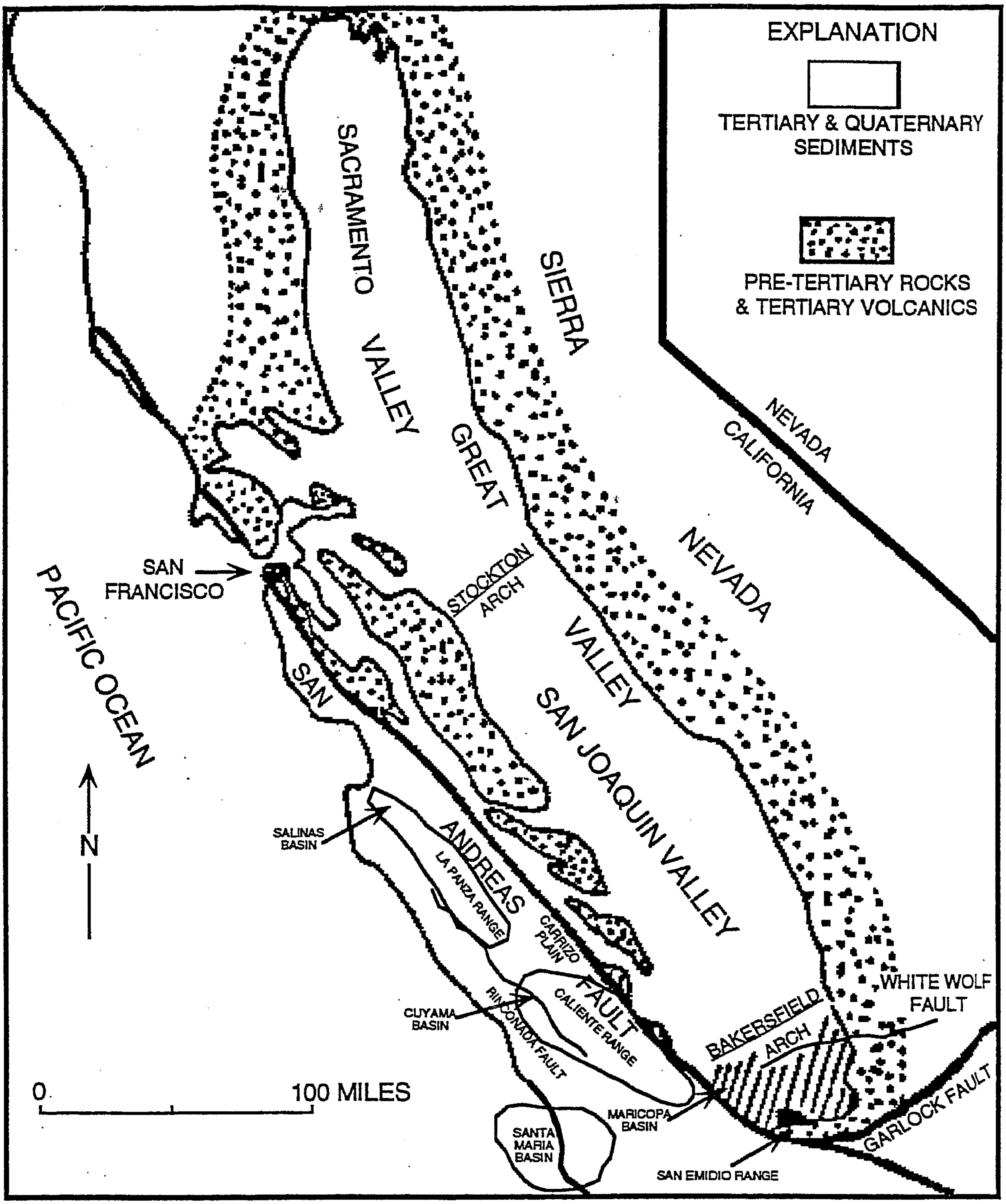

Figure 3–1 Great Valley of California showing important faults, mountain ranges, and major petroleum basins. Modified from Bazeley (1972); Thurston, Mason, and James (1987).

Table 3-1 Class 4 Fields with Shoreline Barrier Island Deposits in California with Production Statistics (TORIS).

Field Name	Reservoir	Formation	# Wells	Porosity %	Perm. mD	API °	OOIP (bbl)	Depth ft.	Net Pay ft.
Antelope Hills	Williams area	Agua M.Temblor	8	33	698.2	18.9	28,322,500	2300	80
Ant Hill	Olcese	Olcese	30	34	350	13.5	49,651,900	2286	100
Blackwells Corner	Temblor	Temblor	32	33	698.2	12	19,400,000	1211	86
Capitan	Vaqueros	Vaqueros.	7	21	2500	22	32,677,010	1400	135
Capitan	Covarrubias	Sespe equivalent	1	20	158	40	12,788,200	3000	200
Cat Canyon West	Alexander	Sisquoc	8	28	1000	22.6	29,310,800	3844	88
Cuyama South	Homan	Vaqueros	117	28	215	32	830,339,100	4000	300
Edison	Vedder/Freeman	Vedder/Freeman	82	27	1000	39	226,066,000	5420	28
Greeley	Vedder	Vedder	8	20	423	37	180,717,000	11260	122
Jasmin	Cantleberry	Vedder	30	35	1055	13	20,722,100	2800	26
Kern Bluff	Miocene sediments	Santa Margarita	15	29	5000	15	61,300,100	1082	70
Mount Poso	Upper Vedder	Vedder	192	33	2200	16	252,353,000	1800	59
Oakridge	Miocene sediments	Toganga/Vaqueros	30	30	135	20.4	45,759,500	2450	90
Placerita *	Pliocene	Pico							
Pleito	Creek area	Santa Margarita	24	25	50	17.6	30,084,300	4000	125
Rosedale Ranch	Lerdo	Etchegoin	8	30	1250	17	64,296,100	4370	82
Round Mountain	Coffee Canyon	Vedder/Pyramid H.	39	32	1500	16.9	50,601,600	1500	82
Round Mountain	Round Mountain	Freeman/Jewett	150	35	170	21.3	279,288,100	1791	72
Round Mountain	Vedder	Vedder	169	35	6000	15	175,413,000	2300	67
Russell Ranch	Dibblee sands	Vaqueros	56	23.9	122	32	214,400,000	3000	130
San Ardo	Auriquac	Monterey	363	34	2200	12	439,205,100	2350	100
San Ardo	Lombardi	Monterey	167	33	5000	11	1,070,190,000	2122	133
Shiells Canyon	Eocene sediments	Llajas	32	10	1	33	38,527,900	4800	600
Summerland Offshore	Vaqueros	Vaqueros	26	20.8	156	33.8	64,659,200	7937	118
Tejon-Tejon Grapewine	western area	Santa Margarita	78	29	2000	15.8	56,071,900	2649	55
Wayside Canyon *	Pliocene sediments	Pico							
Wheeler Ridge	central area	Fruitvale	9	29	363.1	22.3	24,769,390	2350	100
White Wolf	Reef Ridge Mem.	Monterey	20	30.8	393	14.4	29,304,700	2500	100
AVERAGE				28.404	1332.2			3251	121.1
STANDARD DEVIATION				6.0967	1654.5			2219	111.7

* The Pico Formation is a turbitide and Placerita and Wayside Canyon are incorrectly classified as Class 4

3.2.2 Oligocene-Miocene

3.2.2.1 Vedder-Pyramid Hill-Jewett-Freeman Formations

The major Oligocene formations in the southern California valleys are the Walker Formation and the Vedder Formation. The Walker Formation is a coarse sandstone and conglomerate deposit (Goodman and Malin 1988). The Walker sediments are of continental origin and have no Class 4 reservoirs. The Vedder Formation is a shallow marine unit which intertongues with the Walker as the San Joaquin Basin deepens (Bazeley 1972; Goodman and Malin 1988). Figure 3–2 shows stratigraphic columns from sections north and south of the Bakersfield Arch in the San Joaquin Basin (Goodman and Malin 1988).

Sediments from the Oligocene Vedder the lower Miocene Pyramid Hill, the Middle Miocene Jewett Sandstone, and Freeman Siltstone Formations have been treated as a major play (NIPER/BDM-0027 1994) in the San Joaquin Basin, producing oil from several horizons classified as Class 4 shoreline barrier island deposits (TORIS). Oil fields from the Vedder-Pyramid Hill Play with Class 4 production include: Ant Hill, Edison Greeley, Jasmin, Mount Poso, and Round Mountain (Table 3–1). Figure 3–2 also shows a generalized stratigraphic column of the Maricopa subbasin south of the Bakersfield Arch and the adjacent part of the San Joaquin Basin north of the Bakersfield Arch (Bartow and McDougall 1984), including the fields of the Vedder-Pyramid Hill Play.

The Vedder Sandstone is a well sorted, fine-to-medium grained marine sand and shale deposit of Oligocene Age (Bloch 1986). The sand is subangular and predominately quartzofeldspathic (Hayes 1988). The Vedder is a thick subsurface deposit in the eastern San Joaquin Valley of California (Bloch 1986; Olson 1988). Several outcrops at Poso Creek and Chalk Cliff (Olson 1988) in the southeastern portion of the San Joaquin Valley are up to 750 ft thick (Bloch 1986). Downdip the Vedder thickens to over 1500 ft, reflecting deposition in a period of rapid subsidence (Bloch 1986).

The Vedder Formation is described as a slope, or "ramp," between nonmarine and deep marine deposits (Bloch 1986). Analysis of the diagenetic stages of the Vedder sand indicate a long period of deposition with variations in provenance, environment of deposition, burial, and tectonics (Hayes 1988). The Vedder Sandstone overlies the nonmarine Walker Formation in a transgressive relationship (Bloch 1986; Tye et al. 1991).

The Vedder (upper Oligocene) and Jewett (lower Miocene) sandstones are part of a retrogradational parasequence defined by seismic data. They are predominately alluvial, fluvial-deltaic, and shallow marine facies (Tye et al. 1991). The Jewett Formation, including the Pyramid Hill Sand Member, overlies the Vedder and is lower Miocene in age (Bartow and McDougall 1984). The thick sequence of the Vedder has been described as alluvial, fluvial-deltaic, shallow marine to shoreline barrier in the upper Vedder (Tye et al. 1991; Olson 1988; and Iyican 1991).

The Vedder, Jewett (Pyramid Hill Member), and Freeman Silt (middle Miocene) are the major oil bearing sands in the southern San Joaquin Valley (Bartow and McDougall 1984). Portions of these formations in the Mount Poso and Round Mountain fields have been described as near shore marine, barrier island, or shoreface deposits. Mount Poso is described as a barrier bar sand deposited in a shallow marine environment (Iyican 1991). A stratigraphic column (Fig. 3–2) shows the relationship of these formations to underlying and overlying sediments. The Round Mountain oil field produces from the Upper Vedder and Pyramid Hill Member of the Jewett and the Freeman Silt, not from the stratigraphically higher Round Mountain Silt. The Round Mountain Silt is a Mid-Miocene volcanic ash of bentonite and volcanic detritus (Bartow and McDougall 1984).

By 1991 an estimated 657.5 MM bbl of oil and 221.9 BCF of gas had been produced from the combined fields in the Vedder-Jewett sands (Tye et al. 1991) A major unconformity developed as the Jewett Sand transgressed over the Vedder around 23 million years ago (Olson 1988). A period of rapid subsidence occurred during the Late Oligocene and Early to Mid-Miocene, continuing with the deposition of the Freeman Silt (Olson 1988).

The Vedder Sand is truncated at Pyramid Hill and the Pyramid Hill Member of the Jewett Sand lies unconformably on the Walker Formation (Olson 1988). The Pyramid Hill Sand Member is a coarse "grit," easily recognizable on well logs (Olson 1988). It is primarily subsurface but there is one outcrop at Pyramid Hill. The main Jewett Sandstone is a brown-gray, often micaceous, silty sand with some microfossils and fish scales (Olson 1988).

The main producing horizon at the Mount Poso oil field is the Upper Vedder Sand at a depth of 1800 ft (Iyican 1991). This sand is a barrier bar deposit of lower Miocene age (Iyican 1991). The Mount Poso field is bounded by sealing faults on both the north and east and is a remarkably homogeneous sand (Iyican 1991) with good lateral continuity and no major shale breaks (Stokes et al. 1977). Production began at Mount Poso in 1926, and primary production continued till 1971, when steam drive methods took over to produce the heavy oil (15° API) (Iyican 1991). Oil in place is estimated at 214 MM bbl of oil (Iyican 1991).

The gross pay zone at Mount Poso field is 70 ft, and the net pay zone is 55 ft (Chu 1983). Mount Poso field is 290 acres in extent and as of 1983 had 159 producing wells (Chu 1983). The structure of the Upper Vedder at Mount Poso field is a long, narrow fault-bounded field with a dip of 6° (O'Dell and Rogers 1978). The field is a easterly rising homocline (Stokes et al. 1977). The Upper Vedder sand at Mount Poso field is coarse to medium grained, well sorted, subrounded, and unconsolidated (Stokes et al. 1977). Thin silt stringers occurring in the Upper Vedder may inhibit oil flow within the reservoir (Stokes et al. 1977). Minor faulting also occurs in the Upper Vedder, but pressure mapping indicates no barriers to fluid movement (Stokes et al. 1977). The average porosity for the Upper Vedder Sand at Mount Poso field is 33%, and permeability averages 10 to 20 darcies (Stokes et al. 1977).

Faulting is of major importance in trapping oil in Mount Poso and Round Mountain fields in the Upper Vedder and Jewett-Freeman Formations. Oil fields in the San Joaquin Valley are excellent examples of the influence of major fault systems on oil entrapment and production. The San Joaquin Valley is a foredeep basin formed by major wrench faults, with normal faults on the flank of the Bakersfield Arch (Harding and Tuminas 1989). Faulting in the region of the Bakersfield Arch has trapped approximately 700 MM bbl of oil reserves (Harding and Tuminas 1989).

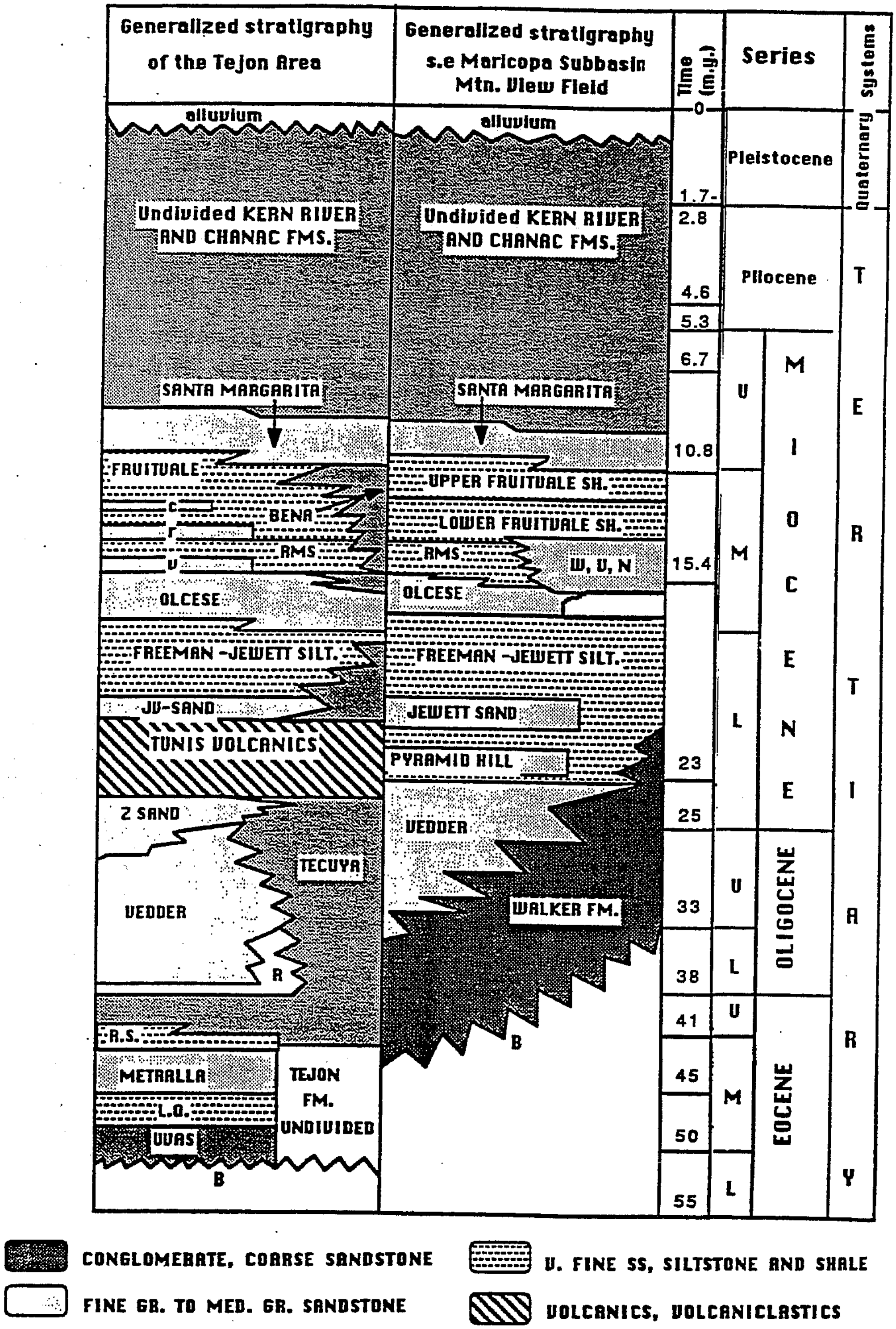

Figure 3–2 Stratigraphic columns for the San Joaquin Basin showing the formations discusssed. Symbols : B=nonconformable contact with underlying Cretaceous crystalline rocks; L.O.=Live Oak Shale; R.S.=Reed Siltstone; R=R Sandstone; V=Valv Sandstone; r=Reserve Sandstone; c= Comanche Sandstone; RMS= Round Mtn. Siltstone; W, V, N= Wicker, Valv and Nozu sandstones, undivided. Modified from Goodman and Malin (1988).

The Round Mountain oil field produces from several zones in the upper Oligocene to Mid-Miocene parasequence of Upper Vedder, Pyramid Hill Member of the Jewett and Freeman Formations. The mechanism for oil entrapment is a complex of normal faults (Harding and Tuminas 1989). As of 1984 the estimated oil recovered was approximately 92 MM bbl (Harding and Tuminas 1989). The sequence of deposits of the Vedder-Jewett sands at Round Mountain field are described as shallow marine facies (Tye et al. 1991). The Round Mountain Main and Coffee Canyon reservoirs are sealed by faulting against down-dropped shales, while the Pyramid Hills reservoir is sealed by a large lateral fault which places the reservoir against crystalline basement rocks (Harding and Tuminas 1989).

3.2.2.2 Vedder-Jewett-Freeman-Olcese and Nozu Formations

Edison oil field in the San Joaquin Valley of California produces oil from numerous horizons from Jurassic metamorphic basement rocks (P'an 1982) to Miocene and Pliocene sedimentary rocks (Sullwold 1953; Schwartz et al. 1981). Since the early 1930s Tertiary oil has been produced from the Oligocene to lower Miocene Vedder, Jewett and Freeman formations, the middle Miocene Olcese and Nozu sands, the upper Miocene Santa Margarita sand and the Mio-Pliocene Chanac Formation (Bartow and McDougall 1984; Sullwold 1953). Production in the 1970s moved into the Miocene and Pliocene argillaceaus and siliceous shales of the Upper Monterey Formation (Schwartz et al. 1981).

In areas of thick Jurassic metamorphics at Edison field, the overlying Miocene sediments are thin (P'an 1982), and the Vedder and Jewett may be absent (Sullwold 1953).

The TORIS database cites extensive production from the Vedder and Freeman formations at Edison and Greeley fields as shoreline barrier island deposition. These are the basal Tertiary formations overlying the Jurassic schists (Sullwold 1953). Edison field is south of the Bakersfield Arch, and the Kern River fields are due north on the north side of the Bakersfield Arch (Bazeley 1972). Greeley field is west of the Kern River fields and north of the Bakersfield Arch. Greeley field produces from a much greater depth (11,260 ft) than any other Class 4 reservoir reported from California (TORIS).

Ant Hill field produces Class 4 oil from the Olcese Formation (TORIS). The Olcese Sandstone (Fig. 3–2) lies above the Freeman-Jewett silt and sandstones and below the Round Mountain Silt in the Maricopa Subbasin (Goodman and Malin 1988; Bazeley 1972).

Olson (1988) describes the relationship of the Olcese Sand as interfingering with both the Freeman Silt and the Round Mountain Silt. The Lower Olcese Sand is a gray, fine-grained silty sandstone of marine origin. The Middle Olcese Sand is nonmarine grading to shallow marine in the western section. The Upper Olcese Sand is a very fine to fine-grained sandstone of marine origin. The most likely unit of the Olcese to have a shoreline barrier depositional unit is the Middle Olcese.

3.2.2.3 Vaqueros Formation

The Vaqueros Formation is a major play (NIPER-BDM 0027 1994) in the Cuyama Basin of equivalent age to the Vedder-Pyramid Hills play of the southern San Joaquin Basin. TORIS lists the following fields as producing oil from Class 4 reservoirs in the Vaqueros Formation in the Cuyama Basin; Capitan, Cuyama south, Oakridge, Russell Ranch and Summerland, offshore (Table 3–1).

The Vaqueros Formation is a Late Oligocene to Early Miocene age transgressive sequence of marine strata located in the Cuyama Basin (Lagoe 1984). Figure 3–1 shows the positions of the major southern California oil producing basins. The Vaqueros has a variable basal contact with the Sespe Formation ranging from unconformable to gradational, moving from west to east (Edwards 1971). Subsidence along the basin margin surrounded by fluvial systems caused the development of barrier bars in the Vaqueros (Edwards 1971). The sands of the barrier bars are coarse-grained and cross-bedded (Edwards 1971).

The lowest unit in the Vaqueros is the Quail Canyon Sandstone Member, which outcrops only in the southeast Caliente Range, but is widespread in the subsurface of the Cuyama Basin (Bartow 1978). The Quail Canyon Member overlies the continental deposits of the Sespe Formation (Edwards 1971). The transgressive Quail Canyon Sandstone deposition began the development the Cuyama Basin (Yeats et al. 1989). Bartow (1978) described the Quail Canyon Sandstone as fine-to-medium grained sandstone, cross-bedded with abundant molluscan fossils. The lithology and marine fossil content suggest a shallow marine environment of deposition (Bartow 1978). The Quail Canyon Member has a maximum thickness of 64 ft in the subsurface (Bartow 1974). The Quail Canyon is absent under much of the Cuyama Valley, but is present along the margins in the South Cuyama oil field and the Taylor Canyon oil field (Bartow 1974).

In the southeastern Caliente Range, the Quail Canyon is overlain by the Soda Lake Shale Member of the Vaqueros Formation (Bartow 1978). Further to the northwest, the Soda Lake lies directly on the Simmler Formation. Along the margins of the Cuyama Basin the Vaqueros is thin, but it becomes thicker, from 681 to 812 ft at the extreme southeast and northwest portions of the Caliente Range (Bartow 1974). The thin peripheral areas of the Vaqueros in the La Panza Range are not differentiated into members (Bartow 1978). A stratigraphic column for the Vaqueros Formation (Fig. 3–3) shows the basic relationships of the Cuyama Basin rocks in the Caliente Range.

The Soda Lake Shale Member of the Vaqueros Formation outcrops in the northwestern and southeastern portions of the Caliente Range. At the type section overlying the Simmler Formation the Soda Lake Member is 115 ft thick (Bartow 1974). It reaches a maximum thickness of 183 ft in the southeastern part of the Caliente Range (Bartow 1974). East of the Caliente Range, the Soda Lake thins and intertongues with the Painted Rock Sandstone Member of the Vaqueros, which is stratigraphically higher. The Soda Lake Shale is typically a hard, dark gray to grayish-brown siltstone with platy shale and thin sandstone beds interspersed (Bartow 1974). As the Soda Lake thins eastward, it becomes progressively more sandy (Bartow 1974).

The Painted Rock Sandstone Member of the Vaqueros Formation is a thick clastic unit of shallow marine origin (Yeats et al. 1989). Northeast of the Big Spring thrust fault, the Painted Rock Member is up to four and one-half times thicker than the section southwest of the fault. At Caliente Mountain the Painted Rock Sandstone is more than 232 ft thick (Bartow 1974). In the southwest section, the Painted Rock thins to 32 ft over the granitic basement high, where both the Quail Canyon and Soda Lake Members are absent (Bartow 1974).

The Painted Rock Member has large bodies of medium- to very thick- bedded fine-to coarse-grained pale-greenish gray to yellowishgray sandstone (Bartow 1974). Channel fill structures at the base of the Painted Rock are very coarse sand, with poorly sorted pebbles and cobbles (Bartow 1974). The uppermost Painted Rock Member at Padrones Canyon is a laminated and well-sorted sandstone

(Bartow 1974). Cross-bedding in the Painted Rock Member is common in the central Caliente Range with medium to large scale tabular cross-beds (Bartow 1974).

Yeats et al. (1989) demonstrate that major faults in the Cuyama Valley cut the La Panza Range and Caliente Ranges. Figure 3–3 shows the stratigraphic relationships of the Vaqueros and Monterey Formations in the Oligocene and Miocene development of the Cuyama and Salinas Valleys of California (Bartow 1990).

The Vaqueros Formation was deposited during a rapid transgression from Late Oligocene to Early Miocene (Osborne and Fritsche 1987). The eastern section was a fluvial-deltaic system, while the western section was a wave-dominated erosional coastline (Osborne and Fritsche 1987). The western section has marine deposits ranging from offshore to backshore, and the eastern section is prodelta, delta front, and delta plain (Osborne and Fritsche 1987). The western offshore and shoreface deposits lie unconformably over the nonmarine Sespe Formation (Osborne and Fritsche 1987). Rigsby (1989) subdivides the western section of the Vaqueros paleogeographically into barrier/spit, outer shoreface, and inner shelf environments. Sediment reached the Vaqueros shelf from two directions: the mainland to the east and the partially emergent trench-slope break in the west (Rigsby 1989a). The sediments included Salinian granitic rocks, Francisian rocks from the north, and granitic and volcanic rocks from the southeast (Edwards 1971). These were deposited in shallow water in the rapidly subsiding basin (Edwards 1971).

The Oligocene sandstones of the Vaqueros Formation at Capitan and Hondo oil fields are defined as shoreline sandstones and conglomerates and inner shelf sandstone facies (Rigsby et al. 1991). Outcrops of the inner shelf sand are burrowed, cross-bedded, gravely sandstones (Rigsby et al. 1991). At Hondo field the base of the Vaqueros shows a sharp grainsize change from interbedded fluvial-deltaic sands of the Sespe Formation to inner shelf sands of the Vaqueros (Rigsby et al. 1991). The complexity of the deposition of environments seen in a tract across the Santa Ynez Mountains including Hondo and Capitan oil fields is due to the interaction of sedimentation and tectonics in a tectonically active depocenter (Rigsby et al. 1991).

The Vaqueros Formation in the western Santa Ynez Range has three distinct facies. The basal unit facies A is coarse conglomerate. Facies B is sandy pebble to pebble-conglomerate with numerous marine fossils. Facies C, the uppermost unit, is highly bioturbated, cross-bedded pebbly coarse sandstone (Rigsby 1989b). Facies A and B represent distal fan delta and braid-delta environments, deposited in braided fluvial (A) and channel mouth (B) conditions (Rigsby 1989b). The sandstones of facies C are shoreface to inner shelf environments (Rigsby 1989b). Sediment was deposited on the Vaqueros shelf from the mainland in the east and from the partially emergent trench-slope break in the west (Rigsby 1989a). Paleographic reconstruction along the Chimineas-Russell fault through the Cuyama Basin was used to prove the two sources of sediment from the Soda lake anticline to the west and the Caliente Range to the east (Bartow 1990). As transgression crossed the area the western shoreline was drown producing filled incised valleys, and backstepping barrier shoreline deposits in the eastern region (Rigsby 1989a). The Vaqueros Formation in the western Santa Ynez Mountains was overwhelmed by tectonic subsidence and shows a succession of deepening upward deposition from deltaic to near shore and shoreline environments (Pinkerton and Rigsby 1991). The overlying Ricon Formation continues the transgression from forearc basin shelf, slope to bathyal environments (Pinkerton and Rigsby 1991).

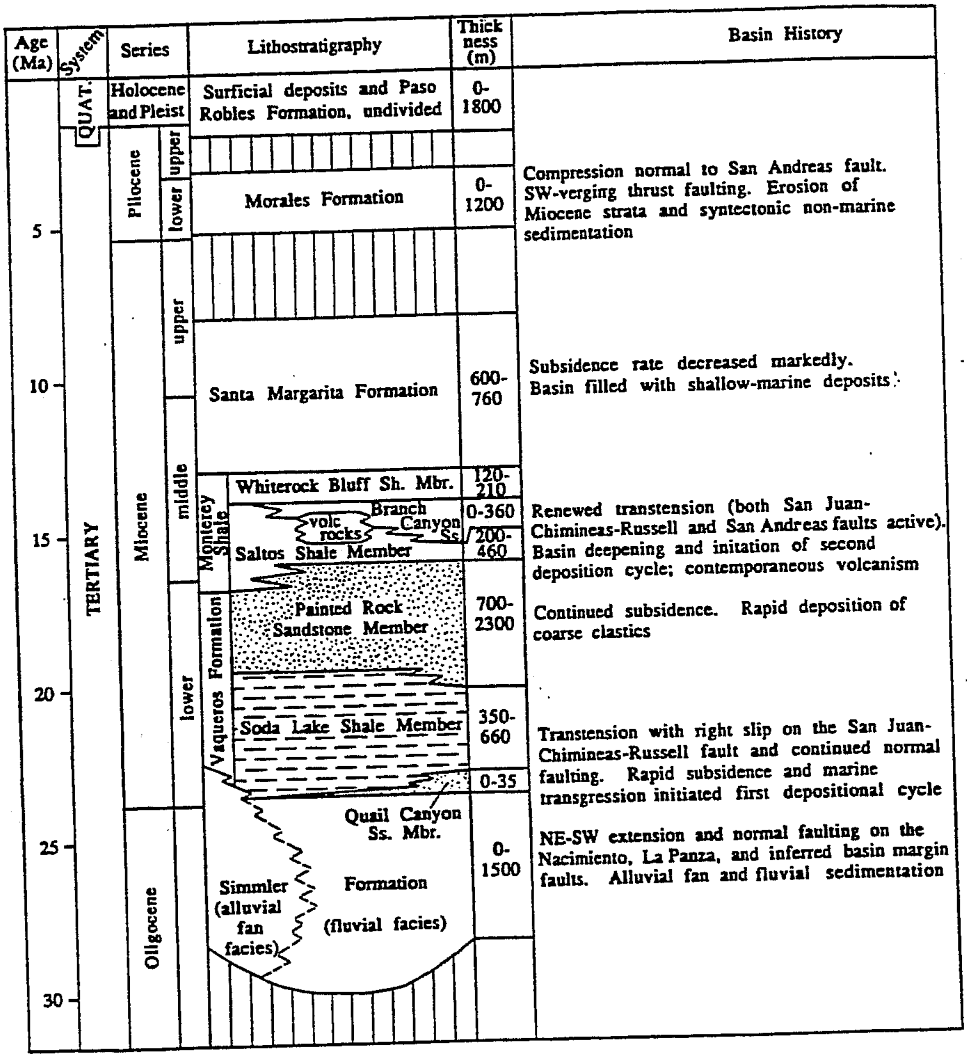

Figure 3–3 A stratigrapic column of the northwestern Cuyama Basin showing the basin history (Bartow 1990).

The Vaqueros Formation in the Santa Barbara Canyon area is interpreted as nearshore to deltaic deposition (Freitag and Fritsche 1988). In this area the Vaqueros overlies the Simmler Formation and makes the transition from nonmarine to marine (Freitag and Fritsche 1988).

Analysis of the oil produced from fields in the Vaqueros and Monterey Formations with rocks in the region suggest the Soda Lake Shale as the most likely source of oil (Lundell and Gordon 1988). Samples from the three largest oil fields in the Cuyama Basin were tested and the carbon isotopic data and ratios of oil and gas correlate with samples from the Soda Lake Shale (Lundell and Gordon 1988). Geochemical analysis of vitrinite reflectance and weight percent hydrocarbon yields indicate that the Soda Lake Shale is the source of oil for all the Southern Cuyama Basin fields (Kormachi 1988). Oil was most likely generated in the deep extensional basin of the Morales-Big Spring thrust system and migrated into the immature Soda Lake Shale (Lundell and Gordon 1988).

The South Cuyama and Russell Ranch oil fields in the southern Cuyama Basin produce light oil from 30° to 40° API from the Dibblee and Colgrove reservoir sandstones of the Vaqueros Formation (Kormachi 1988). The lower Miocene Dibblee reservoir sandstone at Russell Ranch field has been interpreted as shoreline barrier island deposition (TORIS). Russell Ranch and South Cuyama oil fields lie east of the Russell Fault and west of the Caliente Range in the Cuyama Basin (Yeats et al. 1989). The Russell Fault in the subsurface of the Cuyama Basin is the controlling structure on oil production for the entire southern Salinian block of coastal California (Yeats et al. 1989). Movement along the fault began in the Late Oligocene about 23 million years ago (Yeats et al. 1989). The Soda Lake and Painted Rock Members of the Vaqueros were deposited in west-trending, right-stepping trough (Yeats et al. 1989). Isopach maps of the Russell oil field reveals a syncline trending counterclockwise from the Russell fault (Yeats et al. 1989). Folding along the fault trend formed a very thick deposit of the Upper Vaqueros in Russell Ranch field (Yeats et al. 1989). Further evidence of right-lateral displacement along the Russell fault is found in the South Cuyama field where a tongue of shallowmarine sandstone thins and intertongues with the Saltos Shale Member of the Monterey Formation (Yeats et al. 1989) The shearing movement along the fault in the Soda Lake Shale continued through the Miocene and ended with the deposition of the Plio-Pleistocene Morales Formation (Yeats 1987).

3.2.3 Miocene-Pliocene

3.2.3.1 Temblor Formation

Production in the San Joaquin Basin north of the Bakersfield Arch is from Miocene and Pliocene sediments. Thousands of feet of sediments of Miocene age have produced millions of barrels of oil in the 20th century. Several units are classified as Class 4 (TORIS).

The basal unit in the northern San Joaquin Basin is the Temblor Formation (Fig. 3-4). The Agua Sandstone Member of the Temblor Formation unconformably overlies the Painted Rock Sandstone Member of the Vaqueros Formation (Graham and Williams 1985). Antelope Hills and Belridge fields are the main fields producing from the Agua Sand (Graham and Williams 1985), but only Antelope Hills has Class 4 production (TORIS). Antelope Hills oil field is on the western side of the San Joaquin Basin at the base of the Temblor Mountain Range (Dibblee 1973).

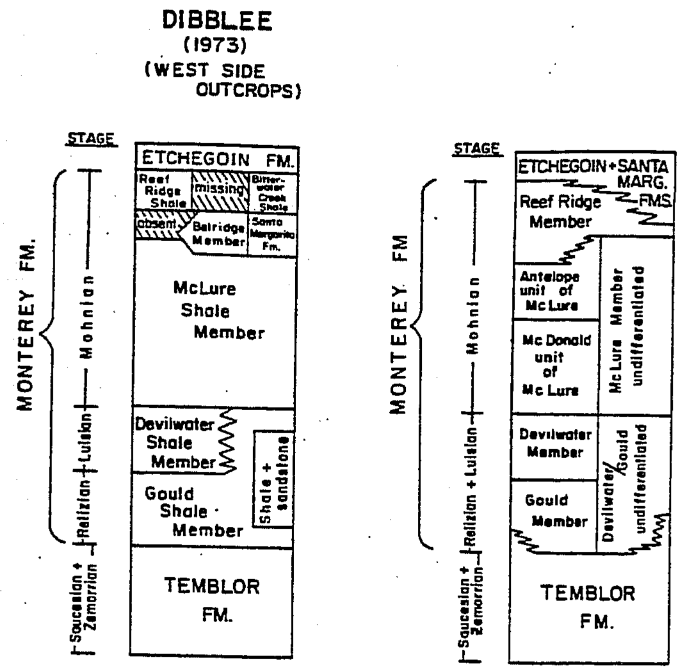

Figure 3–4 A stratigraphic column showing the Temblor and Monterey Formations in the San Joaquin Basin (Graham and Williams 1985).

3.2.3.2 Monterey Formation

The Monterey Formation overlies both the Temblor Formation in the San Joaquin Basin and the Vaqueros Formation in the Cuyama Basin (Dibblee 1973). In the Salinas Basin the lower Miocene Sandholdt Shale Formation separates the underlying Vaqueros Sand from the Monterey Formation. The Monterey is very extensive in southern California, and in some cases has been used historically as a catch-all name for Miocene age clastic sediments of indeterminate origin.

The Salinas Basin (see Figure 3–1) is a 45-mile-long, narrow basin, averaging 6 miles wide with over 15,000 ft of Tertiary sedimentary deposits (Gribi 1963). Class 4 fields with production attributed to shoreline barrier deposits in the Monterey Formation (Table 3–1) include San Ardo and White Wolf fields.

The San Ardo field is one of the major oil plays (NIPER/BDM-0027) in southern California and produces from shoreline barriers in both the Lombardi and Auriquac reservoirs. The Lombardi and Auriquac members of the Monterey Formation at San Ardo field are thick nearly homogenoeous sand units (Baldwin 1953). The Lombardi and Auriquac reservoirs are sometimes classified a formal members of the Monterey, but are more often discussed as lying in undifferentiated upper Miocene sediments (Gribi 1963).

The giant San Ardo oil field has a 400-ft oil column which matches the closure mapped as the top of the Miocene deposits (Gribi 1981). Gribi (1981) described the Miocene surface at San Ardo as sandy strand lines and seaward progressing sand-shale lines, as well as longshore bars and deltaic wedges. Baldwin (1953) identified the thick Lombardi sands as shoreline deposits of a remarkably uniform nature. The Auriquac reservoir is a shallow marine shelf sand (Laing 1988). Structurally the Lombardi and Auriquac reservoirs are stratigraphic traps (Gribi 1981) bounded by the King City fault on the west side of the Salinas River (Miller 1953). The Lombardi Sand is 260 ft thick, and the Auriquac Sand is 200 ft thick; both are unconsolidated (Miller 1953). Since the discovery of San Ardo field in 1946, it has been acknowledged as the largest oil field in California (Baldwin 1953; Gribi 1981). Production has passed 1.5 billion barrels of oil (Table 3–1) from the combined Lombardi and Auriquac reservoirs (TORIS).

Class 4 production (Table 3–1) from the Upper Monterey Formation is limited to White Wolf field (TORIS). White Wolf field produces from the Reef Ridge Member of the Monterey Formation. Reef Ridge is a shale unit at the top of the Monterey which intertongues with the Santa Margarita Formation in the San Joaquin Basin (Fig. 3–4). White Wolf field lies south of the Bakersfield Arch in the Maricopa Subbasin along the White Wolf fault (see Fig. 3–1). The Reef Ridge Sandstone is massive in the eastern part of the basin and thins into four separate bodies in the western section (Bazeley 1972).

3.2.3.3 Fruitvale Formation

The Fruitvale Formation interfingers with and overlies the Monterey Formation in the southern San Joaquin Basin (Fischer et al. 1988). On the eastern slope of the San Joaquin Basin, the Upper Fruitvale interfingers with the Santa Margarita. Wheeler Ridge field (Table 3–1) produces from a Class 4 reservoir in the central area of the Fruitvale Formation (TORIS). Wheeler Ridge field is in the southern San Joaquin (Maricopa Subbasin) north and west of the White Wolf fault (Bazeley 1972). The Fruitvale Shale is described as flanking the Monterey Formation in the San Joaquin Basin

(Fisher et al. 1988). The basin edge has shallower deposits with a terrestrial component (Graham and Williams 1985). The Miocene Fruitvale and Monterey shales are age equivalent, but the shales differ in geochemistry, particularly in kerogen content. (Fischer et al. 1988). Wheeler Ridge field producing from the basin edge Fruitvale Shale has more terrestrial kerogen than does White Wolf in the Monterey Shale (Fischer et al. 1988). Wheeler Ridge field and White Wolf field also have different oil gravities (Table 3–1): Wheeler Ridge, 22.3° and White Wolf, 14.4° API.

3.2.4 Pliocene

3.2.4.1 Sisquoc Formation

Cat Canyon West field is the only Class 4 producing field from the Santa Maria Basin (TORIS). The Santa Maria Basin is located west of the Cuyama Basin and the southern San Joaquin Basin (Loftus 1981) (see Fig. 3–1). The Class 4 reservoir at Cat Canyon field is the Alexander Member of the Sisquoc Formation (TORIS). The Sisquoc Formation is lower Pliocene in age (Crain et al. 1985). The Sisquoc Formation overlies the upper shale units of the Monterey Formation in the northern Santa Barbara channel (Hornafius 1991; Loftus 1981). The main Cat Canyon field produces heavy oil averaging 9° API gravity from one reservoir at 2,500 ft (Loftus 1981). Cat Canyon West field produces a somewhat lighter oil, 22.6° API gravity (Table 3–1), from the Alexander reservoir at an average depth of 3,800 ft (TORIS).

3.2.4.2. Santa Margarita Formation

Further onshore the Santa Margarita Formation overlies the Monterey Shale in the region along the San Andreas fault (Graham and Williams 1985). The Tejon-Tejon Grapewine, Kern Bluff, and Pleito fields (Table 3–1). in the western part of the San Joaquin Basin produce from units attributed to Class 4 deposition (TORIS). The Santa Margarita is primarily a marine sandstone, but west of the Carrizo Plain it grades into nonmarine redbeds (Graham and Williams 1985). Most of the deposition in the Santa Margarita was shallow water marine with some fossils deposited in a regressing sea (Graham and Williams 1985). The Upper Santa Margarita Formation is equivalent to the Lower Sisquoc Formation and is upper Miocene to Pliocene in age (Crain et al. 1985). The Sisquoc is primarily offshore in the western Santa Maria Basin while the Santa Margarita is more widespread and primarily onshore (Crain et al. 1985).

3.2.4.3. Sespe Formation

Overlying the Sisquoc Formation (Crain et al. 1985), the Pliocene-age Sespe Formation offshore and its equivalent onshore have one producing horizon at Capitan field. The Covarrubias reservoir at Capitan field produces oil from a depth of 3,000 ft from shoreline barrier sandstone (TORIS). Capitan field also produces from a barrier island deposit in the Miocene Vaqueros Formation at a shallower depth (1,400 ft) closer to the basin margin (TORIS) .

3.2.4.4. Etchegoin Formation

The youngest Class 4 producing horizon in southern California is at Rosedale Ranch (TORIS) in the San Joaquin Basin. Rosedale Ranch field produces from the Lerdo reservoir in the Etchegoin Formation (TORIS). The Etchegoin a shallow marine sandstone deposit of Pliocene age is conformable over the Reef Ridge Shale (Graham and Williams 1985) (Fig. 3–4). The Etchegoin Sandstone is interbedded with siltstone, claystone, and minor pebble conglomerate units and has a maximum thickness of 5,200 ft at Reef Ridge north of Coalingua in the Maricopa Subbasin (Graham and Williams 1985)

4.0 TEXAS

4.1 Introduction

Since the breakup of the Pangean supercontinent, the portion of the North American continent which includes present-day Texas has lain at the southern edge. Shallow continental seas covering present-day Texas during the Cretaceous were gradually filled during the Cretaceous and Tertiary by sediment brought into the region by river systems with headlands in the Rocky Mountains to the west and the Appalachian Mountains to the east. The fluvial, deltaic, and shelf sediments formed by these systems accumulated in the East Texas and Texas Gulf Coast Basin. The Texas Gulf Coast Basin is divided into the Rio Grande Embayment to the south and the Houston Embayment to the northeast by the San Marcos Arch (Fig. 4–1). Strandplain and barrier island sediment were deposited as part of the Paluxy and Woodbine Groups during the Cretaceous in the East Texas Salt Basin and as part of the Jackson Group and Frio Formation in the Texas Gulf Coast Basin (Fig. 4–2). A comprehensive tabulation of strandplain/barrier island characteristics for Texas reservoirs is provided in Table 4–1.

4.2 Mesozoic Stratigraphy

4.2.1 Cretaceous

The Mesozoic strandplain/barrier island deposits in Texas from which petroleum has been produced are restricted to the Cretaceous. All of the major fields producing from these Cretaceous sandstones are in eastern Texas and southern Texas.

4.2.1.1 Paluxy Formation

The Paluxy strandplain sandstones were formed during a major influx of clastics from the continental interior into the East Texas Salt Basin. The Paluxy has been divided into distal and proximal barrier sandstones. The proximal facies was formed closer to the source of sediment to the north and exposed to greater wave action whereas the distal facies was deposited farther from the source and in deeper water. The proximal coastal-barrier subfacies is characterized by thicker clean porous sandstones from 40 to 100 ft thick, separated by thinner lenses of mudstone and shale. The distal coastal-barrier subfacies is composed of thin strike-oriented fine-grained to silty sandstones from 3 to 60 ft thick and interbedded shale and mudstone constituting at least half of the total thickness of the section (Caughey 1977).

The proximal facies of the Paluxy has a slightly higher porosity, a significantly higher permeability, and lower initial water saturation, and a slightly lower recovery efficiency than the distal facies (Table 4–2). These differences are directly related to the better sorting and lower clay and silt content of the proximal facies.

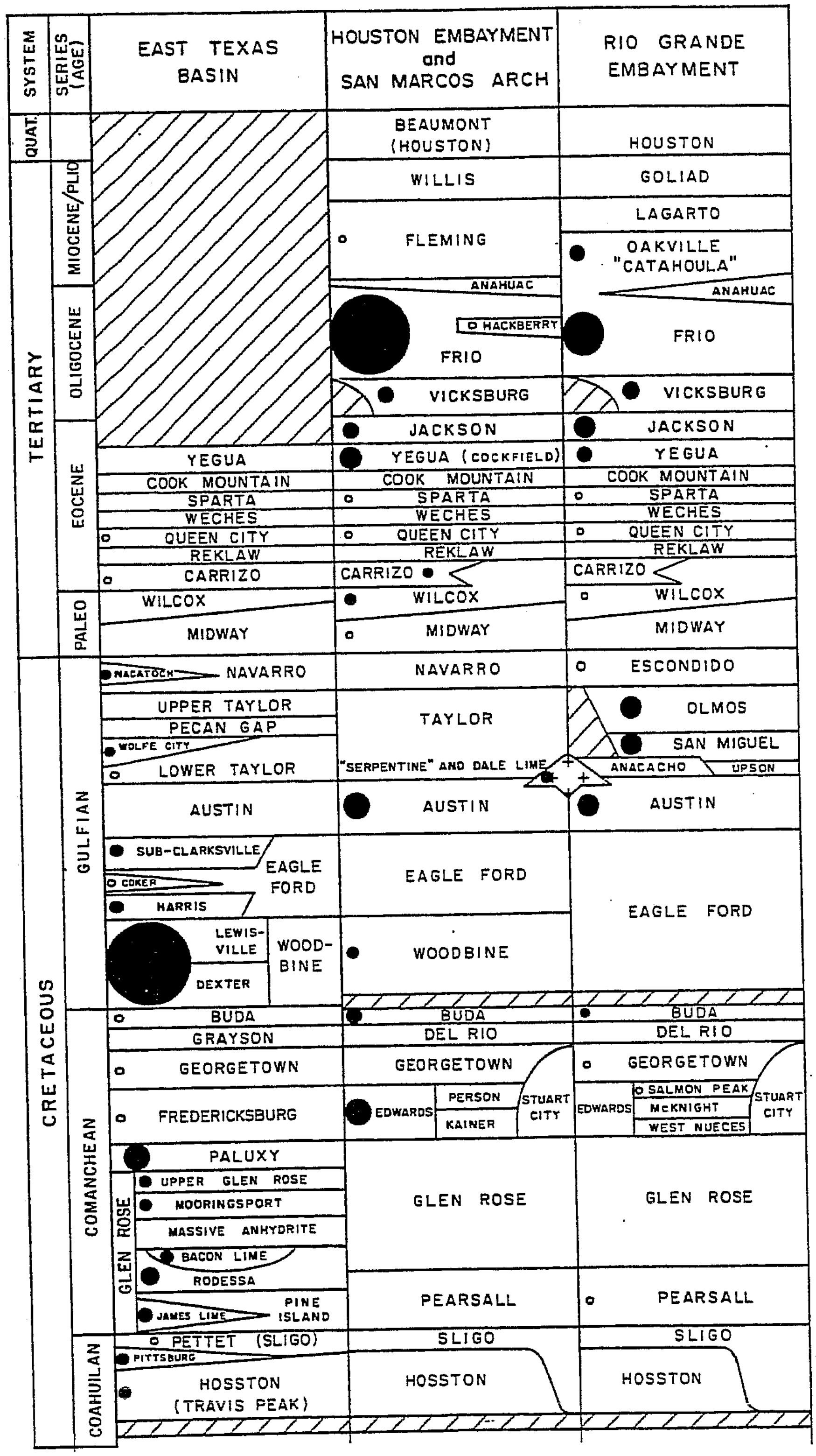

Figure 4–1 A stratagraphic column of Texas showing the formations discussed. Solid circles indicate relative cummulative oil production. Crosses indicate intrusive volcanic formations (Galloway et al. 1983).

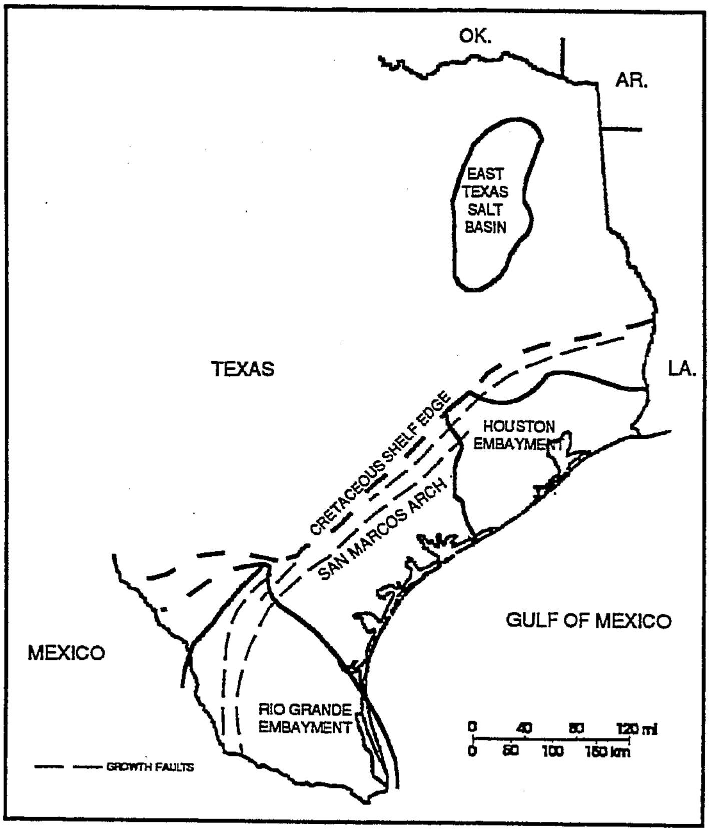

Figure 4–3 An index map of Texas showing the strandplain/barrier island reservoirs and formations. Modified from Tyler et al. (1984); Galloway et al. (1983).

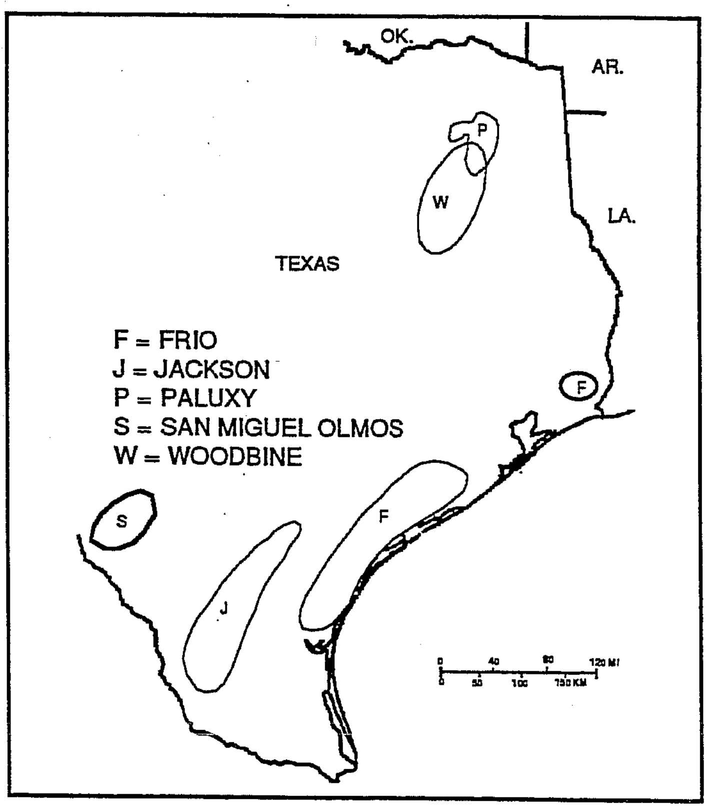

Figure 4–2 An index map of Texas basins showing the basins with areas of strandplain/barrier island deposition. Modified from Tyler et al. (1984); Galloway et al. (1983).

Table 4-1 Oil Fields with Shoreline Barrier Island Deposits in Texas giving Production Statistics (TORIS).

Field Name	Reservoir	Formation	Porosity %	Perm mD	Depth ft	Net Pay ft.	Cum Oil bbl
Armstrong	Brennan		24	80	3650	10	3,966,430
Arnold David	Chapman Sand	Chapman	30.9	500	6010	10	10,521,400
Atkinson	Recklaw	Recklaw					
Aviators	Mirando Sand	Jackson	32	400	1700	16	10,330,000
Baldwin		Frio	32	460	3900	24.1	4,107,250
Beaumont			37.6	4132	5640	15	5,464,940
Benavides			32	478	4700	5	23,337,121
Blessings	F-14-B	Frio	27	102	8200	12	9,318,710
Blessings	F-3	Frio	31	102	7010	18	5,860,740
Bloomington	4600	Frio	27	1000	4600	30	31,663,100
Bonnie View	Bonnie View	Anahuac	34	1000	4575	20	19,593,300
Campana, S.		Jackson	34	400	3020	22	9,456,900
Carthage	Burnett Sand		20	100	5882	20	10,735,190
Cedro Hill	Cole Sand	Jackson	35	800	1440	12	6,569,220
Chapel Hill	Fredricksburg	Paluxy	23	276	5680	20	7,427,480
Coke	Sub Clarkville	Eagleford	28	494	4077	17	7,628,560
Coke	Paluxy	Paluxy	22	1175	6310	55	29,151,600
Cole, W.	Mirando Sand	Jackson	29	850	2375	16	5,020,400
Coletto Creek	2800' pool	Frio	33	500	2776	28	12,337,800
Conoco Drisco	Upper 1st G		31	1146	3300	13	15,208,600
Corpus Christi			22.5	40	4070	26	6,804,300
Corsicana	shallow		39	1700	1125	14	43,113,390
Eagle Hill		Jackson	33.1	1521	1500	7	5,717,780
Elpar	F-07 E.	Frio	17	30	5131	15	8,383,530
Encino	6400 sand		33	4310	6390	6	3,845,780
Escobas	Mirando sand	Jackson	30	500	1200	20	13,046,900
Ezzell			30	506.3	1500	7	6,938,260
Fitzsimmons			27.5	95	4303	10	5,588,260
Flour Bluff	Massive, Up.		30.9	633	6800	11.2	7,471,740
Forest Hill	Harris sand	Woodbine	28	740	4800	13	13,100,000
Francitas, N.		Frio	27	1800	8500	30	11,682,500
Ganado		Frio	26	1400	5080	42	35,700,000
Ganado Deep	Hultquist	Frio	31	5250	6665	35	24,300,000
Gando, W.	4700 zone	Frio	33.6	1411	4730	44	43,111,100
Goverment Wells	Govt. Wells	Jackson	31	550	2200	25	106,000,000
Greta	4400	Anahuac	33	1000	4400	20	134,236,000
Ham Gossett	East	Woodbine	25	1350	3253	13	5,919,800
Heyser	5400 No. 2	Frio	24	215	5428	35	48,072,300
Heyser	5400 No. 3	Frio	30	800	5450	15	27,026,100
Hitts	Paluxy	Pauuxy	20	400	7200	30	13,195,600
Hoffman	L. Cole	Jackson	30	750	2000	9	18,046,300
Hoffman	Loma Novia	Jackson	30	780	2733	10	8,463,300
Jennings	Mirando	Jackson	32.7	590	1200	22	6,680,520
Jennings, w.	30000 sand	Jackson	25	60	3015	8	5,452,740
Kerens, S.	Woodbine	Woodbine	26	505	3384	10	9,062,590
La Rosa	5900 sand	Frio	31	1682	5900	16	11,442,000
La Ward, N.	Frio	Frio	30	200	5200	10	19,409,500
Lake Pasture	Ft-569	Frio	33	1285	5748	7	7,800,660
Lake Pasture	H-440	Frio	32.7	1197	4491	50	50,231,100
Las Animas	Cole	Jackson	30	1800	1800	15	3,401,680
Lolita	Marginulina zone	Anahuac	29	164	5250	5	17,572,210
Lolita	Toney zone	Anahuac	25	100	5700	5	2,704,340
Lolita Deep	4 way zone	Frio	29	363	6333	20	18,000,000
Loma Novia	Loma Novia	Jackson	29	600	2750	16	48,527,300

Field Name	Reservoir	Formation	Porosity %	Perm. mD	Depth ft	Net Pay ft	Cum Oil bbl
London Gin	Doughter sand	Frio	32	1698	4496	15	16,337
Lopez	Mirando sand	Jackson	32	500	2250	22	31,296,800
Louise		Jackson	30	2753	6467	30	9,068,170
Lovells Lake	Frio 2	Frio	28	500	7861	18	30,508,210
Lucille	Hockley upper		30.1	224	3237	12	5,347,490
Lundell	Cole sand	Jackson	32	2630	1550	12	10,357,800
Lundell	Pettus	Yegua	29	302	2490	15	5,975,850
Manziel	Paluxy	Paluxy	26	800	6100	56	25,716,400
Magnet Withers	Frio pool	Frio	24.2	350	5482	30	90,599,910
Markham N, E.	Cornelius	Frio	26	750	8400	10	10,443,900
Markham north	Cornelius	Frio	24	750	7740	5	762,097
Markham north	East Cayce	Frio	24	1390	7875	8	8,100,000
Markham north	West Cayce	Frio	27.5	1387	7800	5	2,200,000
Markham north	West Cornell	Frio	28	591	7700	14	14,900,000
Markham north	Carlson	Frio	27	1000	6960	15	11,453,800
Markham north	Cayce	Frio	24	1387	7800	5	7,508,040
Mary Ellen	FQ-40 sand	Frio	33	8200	5856	26	35,312,210
Mary Ellen	Fs-96 sand	Frio	32	3900	5900	10	11,180,000
Maurbro	Marginulina	Anahuac	27	450	5200	9	25,903,300
McFaddin	4400'	Frio	32	738	4339	2	34,765,100
Mexia	Woodbine	Woodbine	25	1600	3100	60	109,205,000
Midfields			25	2600	9127	10.5	7,684,060
Midway Lake		Frio	23.5	804	4495	10	5,905,260
Mirando City	Mirando sand	Jackson	32	1600	1600	20	12,283,200
Mustang Island	6 sand turbidite	Frio	25	190	7610	18	7,776,270
Mustang Island	7-A turbidite	Frio	30	500	7218	10	5,161,440
Mustang Island	8 sand turbidite	Frio	26.8	435	7310	17	9,749,860
Mustang Island	9 sand turbidite	Frio	26	213	7270	9	7,440,270
New Hope	Hill Sand	eagleford	16	61	7400	13	7,128,470
New Hope	Pittsburg	Eagleford	13	210	8100	17	20,085,700
Nome	all sands		29.5	205	7900	19.3	11,274,890
Odem	6700 B		26	797	6750	17	6,046,450
Odem	Odem		28.7	250	5360	59	9,400,000
Ohern	Pettus	Yegua	28	286	2800	23	22,446,400
Oilton	Bruni		30	800	2025	20	2,144,090
Old Ocean		Frio	26.5	672	10678	12.5	45,102,400
Old Ocean	Armstrong	Frio	26	251	10000	14	68,075,500
Old Ocean	Chenault	Frio	27	640	9600	60	10,158,900
Pettus		Jackson	38	579	3900	21	16,493,900
Pheasant S.	8150 B-1		32	450	8150	8	3,647,060
Phoenix Lake			31.9	1063	7981	14	5,083,140
Pickett Ridge	Frio	Frio	38	1200	4710	10	16,049,100
Piedre Lumbre	Govt. Wells	Jackson	32.5	288	1950	18	21,094,000
Pittsburgh	Pittsburg	Eagleford	12	7	8000	17	14,917,800
Placedo	4700 sand	Frio	33	908	4700	10	42,972,800
Placedo, East		Frio	27	4180	4750	10	8,347,170
Plymouth		Frio	28	3300	5600	28	88,981,700
Portilla	7300 sand	Frio	30.1	1661	7287	44	12,559,000
Portilla	7400 sand	Frio	27.7	1657	7412	47.1	44,619,900
Portilla	8100 sand	Frio	25	954	8122	38	10,002,600
Powell		Woodbine	26	750	3000	62	131,324,000
Prado	combined zone	Jackson	33	950	3729	65	46,478,400
Prado	Loma Novia	Jackson	31	912	3724	7	377,814
Quitman	Sub-Clarkville	Eagleford	21	30	4100	15	6,942,910

Table 4-1 Cont.

Field Name	Reservoir	Formation	Porosity %	Perm. mD	Depth ft	Net Pay ft	Cum Oil bbl
Quitman		Pauluxy	22	732	6200	55	76,624,300
Quitman North		Pauluxy	21	400	6352	35	4,257,230
Randado	Cole	Jackson	30	400	1225	12.8	5,856,850
Refugio	Heart area	Frio	31	1800	6183	15	8,519,470
Refugio	6200 FB1	Frio	30	1000	6200	15	6,407,210
Refugio-Fox		Frio	32	2201	5800	8	45,745,700
Roche	c sand		30	15	6809	22	9,220,600
Sand Flat		Paluxy	18	277	7000	28	32,501,390
Sandusky	Oil Creek sand		17	238	7187	33	14,831,500
Saxet	deep	Frio	25	592	5500	18	5,000,000
Saxet deep	deep	Frio	27	1279	6919	6	5,595,790
Sejita	Hockley	Jackson	25	256	5776	35	49,000,000
Seven sisters	Govt. Wells	Jackson	25.1	228	2412	12	55,899,410
Seventy-Six South		Jackson	35	1200	1710	16	2,225,980
Seventy-Six	Cole	Jackson	31	1209	1328	7	460,271
Shamburger	Paluxy	Paluxy	21	200	7550	35	29,422,990
Slocum	Carrizo sand	Wilcox	37	2655	530	24	45,000,000
Sugar Valley	Laurence A	Carrizo	25	135	8950	26	9,639,000
Taft	4000' sand	Frio	26.5	1500	4000	30	27,046,800
Tom O'Connor	Cataboula	Frio	32	2201	5800	36	330,576,900
Tom O'Connor	4500 Greta s.	Anahuac	33.2	2290	4380	11	18,598,900
Tom O'Connor	5400 sand	Anahuac	31	816	5450	5	200,962,000
Tom O'Connor	5500 sand	Anahuac	31	816	5500	26	17,673,010
Trix Liz	Woodbine B	Woodbine	23	81	3590	20	1,381,320
Trix Liz	Woodbine D	Woodbine	30	1260	3750	30	33,000,000
Volpe	Lopez	Jackson	30	300	2450	17	2,989,660
West Ranch	41-A	Frio	31	895	5730	27	81,350,610
West Ranch	98-A	Frio	29.8	297	6100	21.4	43,995,200
West Ranch	Glasscock	Frio	29	394	5491	19	38,698,000
West Ranch	Greta sand	Anahuac	31.9	1000	5100	40	88,894,190
West Ranch	other zones	Frio	27	250	5600	4	3,515,910
West Ranch	Toney	Frio	32	300	5450	10	23,000,000
West Ranch	Vanderbilt S.	Frio	35	75	6228	12	5,592,450
West Ranch	Venado zone	Frio	31	895	5800	28	5,212,890
West Ranch	Ward	Frio	31	1228	5650	12	21,653,300
White Point, E.		Frio	27	460	5665	76	196,522,000
White Point	14600 Het	Frio	27.5	558.5	4627	3.6	3,165,230
White Point	15000 sand	Frio	31.4	1033	5000	13.8	5,090,000
Withers, north		Frio	25	3266	5100	60	50,206,990
Wortham		Woodbine	27	1620	2900	35	24,935,500
Yantis			20	1300	4200	6	2,621,380
AVERAGE			28.371	995.12	5123.2	20.759	
ST. DEVIATION			4.674	1103.8	2154	14.684	

Table 4-2 **A selection of Paluxy Reservoirs Showing Production Characteristics (Dutton and Garrett 1985; Galloway et al. 1983; Hicks and Foster 1980).**

Field	Dep. Environ.	Depth Ft.	Porosity %	Perm. mD	Water Sat.%	Rec. Eff.%
Pewitt Ranch	Strand Plain	4,300	24	2460	10	39
Sulphur Bluff	Strand Plain	4,500	25	4000	40	46
Talco	Strand Plain	4,300	26	2000	11	37
Coke	Proximal Barrier	6,300	22	1175	28	38
Manziel	Proximal Barrier	6,300	20	830	34	44
Quitman	Proximal Barrier	6,200	22	599	15	45
Hitts Lake	Distal Barrier	7,200	22	400	10	43
Sand Flat	Distal Barrier	7,000	18	277	17	47
Shamburger Lake	Distal Barrier	7,300	21	200	15	67

4.2.1.2 Woodbine-Eagleford

The Woodbine Group is a major regressive clastic wedge within the Late Cretaceous carbonates of east Texas. This wedge filled the East Texas Basin that developed west of the Sabine Uplift in the early Late Cretaceous. Near the end of Woodbine deposition, the subsidence of the Sabine Uplift slowed relative to the East Texas Basin, and exposed Woodbine deposits were eroded and redeposited as the Harris Sandstone of the Eagleford Group (Oliver 1971).

The Woodbine-Eagleford is divided into five depositional systems: (1) Pepper, (2) Freestone, (3) Dexter, (4) Lewisville, and (5) Harris, laid down on the shelf north of the Angelina-Caldwell flexure. The Pepper is an extremely widespread prodeltaic-shelf system composed of turbidite sandstones, overbank facies, and interchannel hemipelagic mudstones (Foss 1979). The Freestone is composed of sediment laid down by a wave-dominated deltaic system consisting of channel mouth bar sandstones, coastal bar sandstones, and prodeltaic mudstones. The Dexter fluvial system is composed of tributary channel and meander belt facies. The Lewisville strandplain system is composed of shoreface sandstones and mudstones and associated tidal facies (Johnson 1976). The Lewisville Member sandstones were deposited as a barrier complex south of the main basin from a source to the east. This complex includes tidal channel and delta facies along with washover, lagoonal, and bay facies (Hobday and Perkins 1980). The Harris deltaic/strandplain system consists of wave-or tidal-dominated braided distributary delta, offshore turbidite and tidal reworked turbidite bars, and delta front and strandline bars (Berg and Leethem 1985; DeDominic 1988).

Parts of the Woodbine-Eagleford deposits were exposed to freshwater diagenesis during lower Cretaceous uplift. This event caused the early development of calcite, cement followed later by dissolution of the calcite cement, feldspar, and volcanic clastics while causing the precipitation of kaolinite, chlorite, and quartz overgrowths. This process produced an overall increase in porosity (Turner and Conger 1981).

Table 4–3 shows the marked difference in the characteristics of the reservoirs formed in the different depositional facies of the Woodbine-Eagleford. The porosity, permeability, and recovery efficiency decrease from the strandplain to the wave-dominated deltaic to the offshore bar environments, whereas on the average, the water saturation increases.

Table 4–3 A Selection of Woodbine-Eagleford Reservoirs Showing Production Characteristics (Dutton and Garrett 1985; Galloway et al. 1983; Hicks and Foster 1980).

Field	Dep. Environ.	Depth Ft.	Porosity %	Perm mD	Water Sat.%	Rec. Eff.%
East Texas	Strand Plain	3,600	25	1,300	14	80
New Diana	Strand Plain	3,700	26	141	34	30
Hawkins	Strand Plain	4,500 -	26	3,394	10	66
Van	Strand Plain	2,700	29	1,000	9	81
Cayuga	Wave-Dom. Delta	4,000	25	500	20	60
Long Lake	Wave-Dom. Delta	5,200	25	1,085	30	60
Mexia	Distal Wave-Dom.	3,000	25	1,600	10	45
Powell	Distal Wave-Dom.	2,900		1,600		51
Wortham	Distal Wave-Dom.	2,900	22	1,620		45
Aggieland	Offshore Bar	9,700	11	0.2	23	
Kurten	Offshore Bar	8,300	15	2	38	19

4.2.1.3 San Miguel-Olmos

The reservoirs of the San Miguel-Olmos fields are within wave-dominated deltaic sandstones. These sandstones were laid down in an aggrading series of arcuate, strike-parallel coastal barriers. Following abandonment of the deltaic system, the upper portions of both the fluviodeltaic and strandplain sands were biogenically and mechanically reworked within deltafront sands and muds. Generally, the dune and beach facies of the strandplain are not preserved (Weise 1980). Tables 4–4 and

4–5 show the low permeability and recovery efficiency of the deltafront sandstone reservoir compared to the sandstones where the beach ridge facies is preserved.

The most common cements in the San Miguel sandstones are calcite and quartz overgrowths. Most of the leaching of feldspars and replacement by calcite occurred at shallow depths. The greatest porosity is in zones of leached shells and feldspars and its distribution is relatively unpredictable (Weise 1980).

Table 4–4 A Selection of San Miguel Reservoirs Showing Production Characteristics (Galloway et al. 1983).

Field	Dep. Environ.	Depth Ft.	Porosity %	Perm. mD	Water Sat.%	Rec. Eff.%
Big Wells	Wave-Dom. Deltafront	5,400	19	6	45	29
Sacatosa	Wave-Dom. Deltafront	1,200	24	4	45	15

Table 4–5 A Selection of Olmos Reservoirs Showing Production Characteristics (Galloway et al. 1983).

Field	Dep. Environ.	Depth Ft.	Porosity %	Perm. mD	Water Sat.%	Rec. Eff.%
Big Foot	Wave-Dom. Deltafront	3,300	27	3	60	26
Somerest	Beach Ridge	1,000	28	85	48	30

4.3 Cenozoic Stratigraphy

The Cenozoic strandplain/barrier island deposits in Texas from which petroleum has been produced are restricted to the middle of the Tertiary. All of the wells producing from these Tertiary sandstones are along the Gulf Coast.

4.3.1 Eocene

4.3.1.1 Jackson Strandplain/barrier Island

The Jackson Group is composed of fluviodeltaic sediments deposited during the Eocene along the Gulf of Mexico Coast in what is now Texas and Louisiana. A strandplain/barrier island system was deposited during this time in what is now south Texas.

The area from the modern Sabine River through the Houston Embayment was dominated by the Fayette fluviodeltaic system. Longshore currents carries sediments debouched into the Gulf of Mexico southwestward-building strandplains and barrier islands along the coast over the San Marco Arch. The barrier system is thin and poorly developed over the arch, but in the Rio Grande Embayment it is much wider. A system smaller than the Fayette was responsible for forming the wave-dominated deltas and associated strandplains and barrier islands of the Rio Grande Embayment.

As the sediments brought into the Rio Grande Embayment loaded the basin, the Wilcox fault system allowed the sediment to slowly subside causing an aggradation of beach front and barrier island deposits. Relative still-stand thick accumulations of sand developed. With a later increase in sediment influx, the system prograded forming thick, wide, tabular sand bodies.

The reservoirs include 8–10 thin, en echelon, strike-elongate sand bodies. Those proximal to the source include flood-tidal and washover facies. Those along the axis of the barrier/strandplain system include barrier-core, barrier-flat, and tidal inlet facies. Reservoirs distal to the source include shore and ebb-tidal facies (Fisher et al. 1970). Table 4–6 shows selected characteristics of the reservoirs. The proximal reservoir sandstones have a slightly higher porosity and permeability than the other facies. However, this may have more to do with their shallow depth and consequent smaller diagenetic alteration than with their location in the depositional system.

Table 4–6 A Selection of Jackson-Yegua Barrier/Strandplain Reservoirs Showing Production Characteristics. (Dutton and Garrett 1985; Galloway et al. 1983; Hicks and Foster 1980).

Field	Dep. Environ.	Depth Ft.	Porosity %	Perm. mD	Water Sat. %	Rec. Eff. %
Aviators Miran.	Proximal	1,700	32	357	37	28
Escobas Mirando	Proximal	1,200	30	500	40	46
Lopez	Proximal	2,200	35	250	40	44
Mirando City	Proximal	1,600	33	1,600	40	26
Colorado Cockf.	Axial	2,600	28	800	25	42
Conoco Driscoll	Axial	2,800	31	458	32	34
Govt. Wells Ngw	Axial	2,200	32	800	30	52
Govt. Wells Sgw	Axial	2,300	30	600	35	45
Loma Novia	Axial	2,600	26	800	25	27
O'hern	Axial	2,700	28	286	20	36
Piedre Lumbre	Axial	1,900	30	300	30	23
Prado	Axial	3,700	32	850	26	62
Seven Sisters	Axial	2,330	28	225	55	39
Hoffman Doughe.	Distal	2,000	34	757	40	38
Pettus	Distal	3,900	38	452	25	37

4.3.2 Oligocene

4.3.2.1 Frio Strandplain/Barrier Island

The Frio Formation is composed of both fluvial deltaic and strandplain/barrier island sandstone. The main area of Frio Class 4 strandplain/barrier island sandstone oil production runs from Kleberg County along the southern Texas Gulf of Mexico Coast, northeast to Brazoria County. South and west of Kleberg County, the strandplain/barrier island deposits grade laterally into the fluviodeltaic deposits of the Rio Grande Embayment. The recent literature tends to include the Anahuac as part of the Upper Frio rather than a separate formation. Data in the TORIS data base and earlier papers site the Anahuac Formation reservoirs as separate from the Frio (Galloway et al. 1983; Tyler et al. 1984; Dutton and Garrett 1985) (see Table 4–1).

Northeast of Brazoria County, in the Houston area, the Frio Formation is composed of sediments deposited in the deeper water conditions of the Houston Embayment. These sediments deposited in both Texas and Louisiana were later deformed by halokenetic tectonics.

The Frio sandstones were formed as shoreline or strandplain deposits and offshore barrier islands in an interdeltaic area along the Oligocene coast of the Tertiary Gulf of Mexico. Most of the sediments derived from gradual tilting of the continental interior were dumped into the Rio Grande and Houston embayments with little sedimentation along the arch between the deltaic systems that filled the embayments. The Oligocene Gulf of Mexico was a restricted body of water with lower wave energies and microtidal range of less than 3 ft along the coast (Galloway and Cheng 1985).

Growth faulting along the margin of the Gulf of Mexico was important in controlling Frio deposition. A series of active, down-to-the-Gulf faults controlled the shoreline position, particularly in the Houston Embayment. The two main fault zones were the Vicksburg to the east and the Frio to the west with minor, local faults near the present-day Texas-Louisiana border.

The Vicksburg and Frio fault zones parallel the interembayment San Marcos Arch. As the deltaic sediment continued to move into the surrounding embayments, the loading caused rapid subsidence and fault growth in the embayments and little accumulation on the arch. The Frio shoreline tended to buildup above individual, deep-seated, growth faults during the Oligocene. This caused thick accumulation of aggradational tidal- and wave- sorted sand deposits. In many cases, multiple stacks of Frio sandstones have allowed a single well to produce from numerous payzones in the Frio interval. In addition, many of the barrier islands formed in the interdeltaic region have prograded to form broad, tabular sand bodies (Galloway et al. 1982).

As movement from sediment loading continued along deep-seated faults, the tabular sand bodies rolled over to form anticlines, which fragmented into separate blocks because of differential loading.

Tables 4–7 and 4–8 show that the reservoir sandstones laid down over the San Marcos Arch in the mixed deltaic facies have on average a slightly lower porosity and permeability than the stacked barrier sandstones. Recovery efficiency is highest from the transgressive sheet sandstones, intermediate in the composite beach-ridge plain, distributary, and deltaic facies, and lowest from the mud-rich beach and chenier plains sandstones (Tyler and Ambrose 1986). The sandstones laid down on the barrier front on average have a lower permeability and recovery efficiency (Table 4–9). Progradational barrier sandstone bodies of barrier core and crosscutting inlet fill with maximum permeability in the barrier core. Transgressive barrier deposits of washover-fan and barrier-flats sandstones have relatively low permeability (Galloway and Cheng 1985). Because of the small number of samples from the Frio in the Houston Embayment, no relationships can be determined among the selected reservoir characteristics (Table 4–10).

Table 47 A Selection of San Marcos Arch, Frio Mixed-Deltaic (M.D.) Reservoirs Showing Production Characteristics (Dutton and Garrett 1985; Galloway et al. 1983; Hicks, and Foster 1980).

Field	Dep. Environ.	Depth Ft.	Porosity %	Perm. mD	Water Sat.%	Rec. Eff.%
Magnet-Withers	M.D.	5,600	29	1,700	27	56
Markham N-Bcn	M.D.	7,000	31	3,333	26	58
Ocean City Arms	M.D.	10,000	26	251	13	51
Ocean City Chen	M.D.	9,600	27	640	24	38
Pickett Ridge	M.D.	4,700	38	312	33	60
Sugar V.-N. Lau	M.D.	8,900	23	600	27	31
Withers North	M.D.	5,300	25	2,500	20	50

Table 4-8 **A Selection of San Marcos Arch, Frio Stacked-Barrier (S.B.) Reservoirs Showing Production Characteristics (Dutton and Garrett 1985; Galloway et al. 1983; Hicks and Foster 1980).**

Field	Dep. Environ	Depth Ft.	Porosity %	Perm. mD	Water Sat.%	Rec. Eff.%
Bloomington	S.B.	4,600	34	1,140	40	46
Bonnie View	S.B.	4,500	30	1,000	30	39
Francitas N.	S.B.	8,500	27	1,800	30	53
Ganado West	S.B.	4,700	33	1,411	38	53
Greta 4400	S.B.	4,400	33	687	27	47
Heyser 5400	S.B.	5,400	24	300	35	54
Lake Pasture H	S.B.	4,500	32	1,197	32	56
La Rossa 5400	S.B.	5,400	29			50
La Rosa 5900	S.B.	5,900	29	1,682		62
La Ward North	S.B.	5,200	26	350	33	29
Lolita Marg	S.B.	5,300	29	164	34	54
Lolita Ward	S.B.	5,900	30	635	31	62
London Gin D.	S.B.	4,500	32	1,698	27	63
Maurbro Marg.	S.B.	5,200	27	450	25	51
Mcfaddin	S.B.	4,400	32	287	25	48
Midway Main	S.B.	5,300	34	4,500	29	28
M.E. O'connor	S.B.	5,900	33	820	22	40
Placedo 4700 Ss	S.B.	4,700	33	847	40	58
Plymouth Heep	S.B.	5,600	28	3,300	20	49
Portilla 7300	S.B.	7,300	29	1,412	33	50
Portilla 7400	S.B.	7,400	28	1,634	27	62
Taft 4000	S.B.	4,000	25	1,500	23	58
Tom O'connor 44	S.B.	4,400	32	578	48	53
Tom O'connor 45	S.B.	4,500	33	2,290	32	56
Tom O'connor 55	S.B.	5,500	31	816	30	54
Tom O'connor 58	S.B.	5,800	32	1,758	16	60
Tom O'connor 59	S.B.	5,900	32	2,136	14	61
West Ranch Glas	S.B.	5,500	29	394	45	42
West Ranch Gret	S.B.	5,100	32	1,000	33	50
West Ranch Ward	S.B.	5,700	32	1,228	42	54
West Ranch 41-A	S.B.	5,700	30	869	28	46
West Ranch 98-A	S.B.	6,100	30	497	30	57
White Point Eb	S.B.	5,700	33	575	38	55

Table 4–9 A Selection of San Marcos Arch, Frio Barrier Front (B.F.) Reservoirs Showing Production Characteristics (Dutton and Garrett 1985; Galloway et al. 1983; Hicks and Foster 1980).

Field	Dep. Environ.	Depth Ft.	Porosity %	Perm. mD	Water Sat.%	Rec. Eff.%
Aransas Pass	B.F.	7,100	28	225	31	47
Flour Bluff	B.F.	6,600	31	745	40	51

Table 4–10 A Selection of Houston Embayment, Frio Reservoirs Showing Production Characteristics (Dutton and Garrett 1985; Galloway et al. 1983; Hicks and Foster 1980).

Field	Dep. Environ.	Depth Ft.	Porosity %	Perm. mD	Water Sat.%	Rec. Eff.%
Amelia	Stacked Barrier	6,800	31	1,390	25	73
Lovell's Lake 1	Shelf Platform	7,700	29	450	40	53
Lovell's Lake 2	Shelf Platform	7,900	29	454	43	72

5.0 COMPARISON OF WYOMING, CALIFORNIA AND TEXAS SHORELINE BARRIERS

5.1 Introduction

The shoreline barrier island facies are the same in all three settings, but differences in age of sediment, basin configuration, sediment input, and diagenesis reveal different aspects in the Class 4 deposits of Wyoming, California, and Texas. The basic facies which identify shoreline barrier island deposits are rarely found in a complete sequence either in ancient deposits or in modern analogs. Gradual changes in a transgressive sequence show lower to upper foreshore and backshore deposits. Figure 5–1 (Szpakiewicz et al. 1991) shows a typical section through a tidal channel bar. The effects of sudden changes, storms forming washovers and channels is shown in Figure 5–2. They demonstrate the interconnectedness of tidal delta deposits as storms breach the outer barrier island and form complexes of backbeach, channels and lagoonal deposits. Within any specific shoreline barrier deposit facies may be absent, truncated or arranged in varying sequences.

In general, because of the slow transgression of the Continental Sea and then massive postdepositional tectonic forces, sequences in the Paleozoic and Mesozoic rocks of Wyoming have shoreline barriers with broader lateral extent traceable in both outcrop and subsurface. In California the rapid sediment input, contemporaneous faulting, and movements caused by plate tectonics have caused the formation of barrier islands with depth, but little lateral expression, and a poor relationship between outcrop and subsurface units. In Texas the continual sediment input into a subsiding basin with low tidal energy has caused the formation of thin, en echelon, elongate barrier islands, which have undergone growth faulting. However, these barrier islands have not been subjected to tectonic movements that might have placed outcrops and subsurface units in close proximity.

5.2 Spatial Comparison

Shoreline barrier island deposits along the western shore of the Continental Sea extend discontinuously for several hundred miles from the southern Greater Green River Basin in southwest Wyoming and north central Colorado to north of the present Montana-Wyoming border in the Powder River Basin (Fig. 2–2). The gradual subsidence of the basins and the transgressions and regressions of the Continental Sea produced a series of strandlines and shoreline barriers over a wide area. The Rock Springs Embayment (Fig. 2–5) had a long period of fill when the succeeding shoreline barriers of the Almond Formation were deposited. Likewise, in the Bighorn and Powder River Basins, numerous widespread shoreline barriers were deposited from the Middle Cambrian Flathead Sandstone to the upper Cretaceous Muddy Formation. The original deposition of the Paleozoic and Mesozoic sediments were in broad shallow basins. Laramide age uplift caused the isolation, narrowing and deepening the Wyoming Basins, but it also caused the exposure of outcrops on basin flanks, which can be correlated with subsurface formations.

The shoreline barrier deposition in the isolated basins of California (Fig. 3–1) followed a different pattern because of the more active and continual tectonic movements in the region. Narrow basins of great depth were formed when strike-slip movements along the transform faults caused rapid subsidence and rapid erosion of surrounding uplands and mountain ranges. Shoreline barriers formed along the basin edges for relatively short periods of heavy sediment input and were rapidly replaced

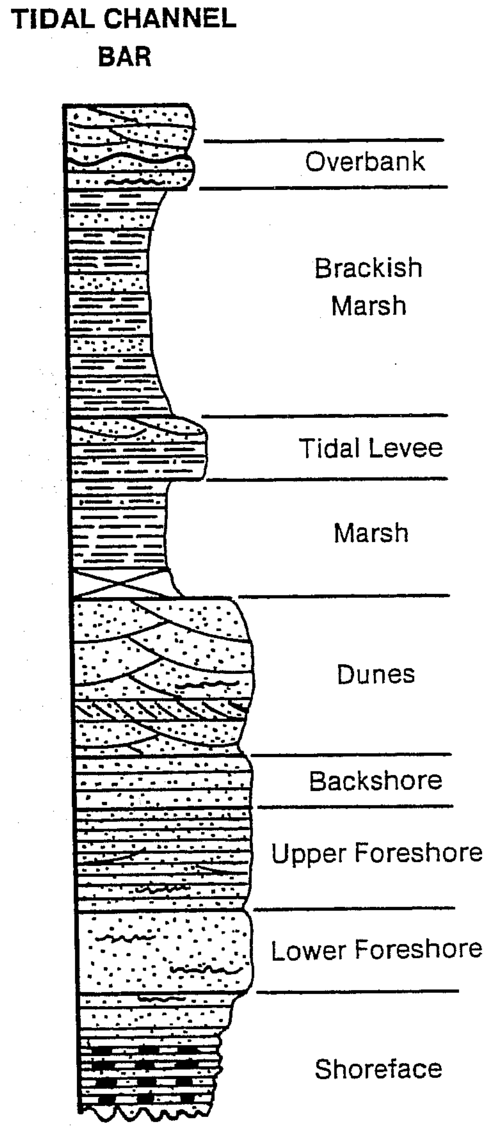

Figure 5-1 Typical regressive sequence of the shoreline barrier sediments in the lower and upper Cretaceous barrier sediments. The sequence represents barrier island facies and backbarrier facies of tidal origin (Szpakiewicz et al. 1991). Modified from Taylor (1980).

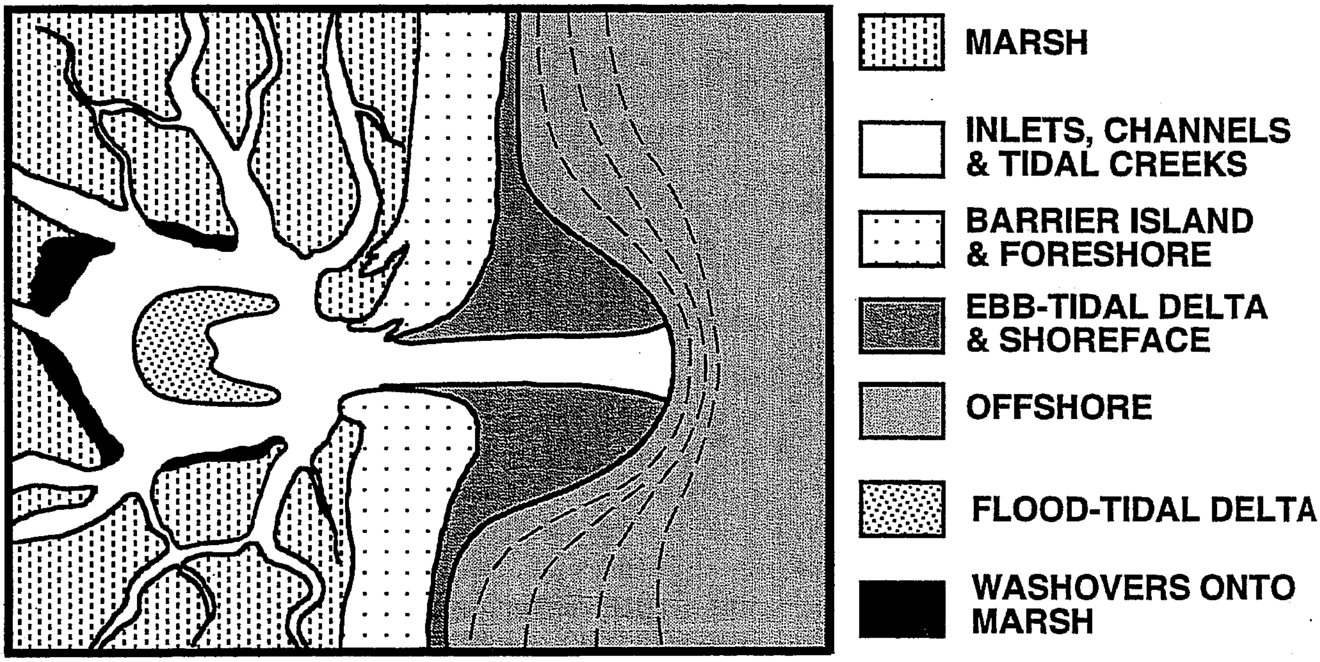

Figure 5–2 A diagram showing the relationship of tidal delta deposits and barrier island facies. Modified from FitzGerald (1988).

with open marine and trubidite flow deposition. The shoreline barrier island deposits of California are thus more discrete, usually of much smaller lateral extend and grade more rapidly into terrestrial on the landward side and shallow marine to seaward.

The Mesozoic and Cenozoic shoreline barriers in Texas are characterized by a thick sediment wedge prograding into the Gulf of Mexico. The major forces affecting the deposition of the formations are differences in sediment input from the Rocky Mountains and Appalachian Mountains, changes in sea level during the different periods of deposition, and the degree of holokenetic tectonics. The sediment input for the Paluxy was from the east into relatively deep water, forming discrete proximal and distal facies. The Jackson tended to form as thin, en echelon barrier islands stacking in shallow water to form wide, thick sand bodies. The heavy sediment input and subsidence during the Frio caused slumping and extensive deep seated growth faulting resulting in thick sand bodies.

Shoreline barriers in Wyoming are characterized by gradual deposition of Paleozoic and Mesozoic sediments in large, but contiguous basins. Paleozoic and some Mesozoic shoreline barrier deposits are found in the Bighorn, Wind River, and Shirley Basins of Wyoming. Most of Wyoming's Class 4 production is found in Cretaceous age reservoirs in the Muddy Formation of the Powder River basin and the Almond Formation of the Greater Green River Basin. In California the areas of shoreline barrier island deposition range over four isolated basins (San Joaquin, Cuyama, Salinas and Santa Maria) and a period of time from Eocene to Pliocene. The numerous fluctuations of the Oligocene and Miocene allowed deposition in many units and over a dozen formations some of limited spatial coverage both vertically and horizontally (Shiells Canyon), and others of greater dimension, such as the thick Lombardi and Auriquac reservoirs at San Ardo field. The Texas barrier islands were formed in a single proto-Gulf of Mexico, in the East Texas Basin in the Cretaceous and in the Houston and Rio Grande embayments of the Texas Gulf Basin in the Tertiary. There is a broad region of coastline in the Texas Gulf Coast which contains the widespread shoreline barriers of the Paluxy, Woodbine-Eagleford, Jackson, and Frio.

5.3 Diagenesis

Because of the differences in age of the sediments and the tectonic histories of the regions (Wyoming, California, and Texas), shoreline barrier deposits show vastly different diagenetic effects. In Wyoming the longer period of burial and influxes of fresh water following the initial saline water deposition and burial, the effects of uplift have caused complex diagenetic changes and extensive cementation. Tectonic activity in Wyoming occurred after deposition and caused deeper burial, separation of basins by uplifts and mountain chains. Wyoming shoreline barrier deposits are well consolidated rocks with complex calcite and clay cementation.

In California the tectonic uplifts, mountain building and faulting was both concurrent with deposition, and continuous following deposition. The much younger age of the California deposits and the different fluctuations of water into the deposits have often resulted in unconsolidated or poorly consolidated sediments. Production histories from the Oligocene Vaqueros and Miocene Monterey note sediments and poorly consolidated rocks in cores from the oil fields.

The diagenetic effects on Texas shoreline barrier reservoirs is greater than those in California sediments, but somewhat less pronounced than those in Wyoming. The lack of tectonic forces has reduced the pressures, compaction, uplift, and erosion tending to affect and enhance the stages of diagenesis. Generally the Texas reservoirs are not as tightly cemented as those in Wyoming. Usually they contain less kaolinite, chlorite and other pore-filing clays than Wyoming reservoirs. The Woodbine-Eagleford underwent a stage of fresh water diagenesis, with early calcite cement formation, followed by a stage of dissolution of calcite cement, feldspars, and volcanic clastics. The overall effect in the Woodbine-Eagleford was to increase porosity and permeability. For reservoir characterization the wide lateral extent of the Almond and Muddy Formations and subsequent uplift and erosion following deposition has allowed surface outcrops of these formations very close (within a few miles) to deeply buried (4000–6000 ft) producing horizons of similar facies of the same formation. The Laramide Orogeny lifted and folded the widespread Paleozoic and Mesozoic rocks and exposed outcrops of deeper basin deposits along the flanks of the uplifts, mountain, and plateaus bounding the intermontane basins. Because of these associations, a much clearer picture of the depositional history and facies relationships can be made.

In California, largely due to strike-slip movement along faults, outcrops of producing formations are often difficult to find, distant from producing zones, and represent different facies. Thus characterization of depositional environments is not as precise, and deposits that may or may not include shoreline barriers are described as shallow marine sands grading into terrestrial deposits.

Facies deposition in Texas shoreline barriers is represented by lateral and vertical stacking of units brought about by changes in sea level and fluctuations in sediment input. The large scale tectonic movements either pentecontemporaneous (California) or postdepositional (Wyoming) did not affect the Texas shoreline barriers. Outcrops of the Frio and Jackson are merely downdip exposures of the formations as the prograding Texas Gulf Coast subsided during the Tertiary.

5.4 Permeability and Porosity Comparison

Table 5–1 gives the averages and standard deviation of the porosity, permeability, depth, and net pay for all the Class 4 reservoirs in Wyoming, California, and Texas. The average permeability and porosity of oil bearing rocks in Wyoming is much less than rocks in either California or Texas. California shoreline barriers are largely unconsolidated or loosely consolidated sediments, permeability is thus relatively high. Wyoming rocks have undergone greater pressures and changes during the Early Tertiary Laramide Orogeny resulting in lower porosity and permeability. Reservoirs in Texas have much higher porosities and permeabilities than those of Wyoming. Average porosities for Texas and California are the same and Texas average permeability is somewhat less than that in California reservoirs due to diagenesis.

Table 5–1 A Comparison of Average Reservoir Characteristics from Wyoming, California, and Texas.

	Aver. Por., %	Std. Dev. Por.	Aver. Perm., mD	Std. Dev. Perm	Depth, Ft.	Std. Dev. Depth	Net Pay, Ft.	Std. Dev. Pay
CALIFORNIA	28.40	6.09	1332.2	1654.5	3251	2219	121.1	111.7
WYOMING	17.10	3.5	95.14	94.33	6606.6	1669.1	23.7	19.56
ALMOND FM.	15	4	10.99	12.27	7322.9	2865.6	31.25	35.9
TEXAS	28.37	4.67	995.12	1103.76	5123.2	2154.02	20.76	14.684

The very low permeability average for the Almond Formation (Tables 2-2 and 5-1) results from the inclusion of both oil and gas production from the Almond. A number of the fields produce only gas or gas and minor amounts of oil from tight gas sands of the Almond Formation (Martinsen and Christensen 1992).

The differences in number of feet in the pay zones from the three regions reflects the basinal configuration and contemporaneous faulting resulting in vertical stacking and thick deposits in California and more lateral deposition and thinner sand bodies in both Wyoming and Texas.

Average depths as expressed in Table 5-1 reflects a wide range of depths, as seen in the standard deviation. Present day depth of a formation or sand body has nothing to do with the original depth of deposition, which was shallow in all barrier island deposits. The Wyoming reservoirs show the greatest depths, demonstrating the length of time over which deposition occurred in the Continental Sea throughout the Paleozoic and Mesozoic. The period of deposition in Texas throughout the Mesozoic and Cenozoic is not as long as that in Wyoming, but each formation represents lengthy deposition in a wide embayment, with relatively great depths caused by subsidence growth faulting. In California the original depth of deposition usually underwent rapid burial, but contemporaneous and subsequent tectonic uplift, erosion, and strike-slip movements have caused a wide range of current depths of the shoreline barriers.

5.5 Background Literature

The literature on geology, particularly environment of deposition and facies relationships for oil reservoirs in Wyoming, is much more complete than corresponding literature from California. Members of the Wyoming Geological Association have published volumes each year since 1949 describing the oil reservoirs of Wyoming. Particularly since the late 1960s these papers have dealt with facies and environmental interpretations.

Literature on oil reservoirs in California falls mainly into three categories: (1) purely stratigraphic descriptions of formations with little or no environmental interpretation, (2) detailed structural geology on faulting and tectonic movements, and (3) engineering papers on methods of increasing production with no reference to geological constraints. Many of the California papers on geology and stratigraphy date from the 1930s to 1950s and do not discuss more modern concepts of facies relationships. More recent California geology deals almost exclusively with fault movements.

The geologic literature on oil-producing formations in Texas is extensive. The Bureau of Economic Geology, University of Texas, and the Gulf Coast Association of Geological Socities (GCAGS) have encouraged research and publication of petroleum geology for many years. Since the 1960s this research has been increasingly directed toward environmental and facies interpretation of the major oil producing Texas formations. Publications from the bureau have focused on comparative and overall studies of major formations and facies relationships and analysis of oil production trends. Papers put out by the GCAGS focus on specific oil fields and facies relationships within formations. Texas reservoirs in the Paluxy, Woodbine, Jackson, and Frio have been more completely analyzed than reservoirs in California. Information on production from different facies of the shoreline barrier in Texas is available from the annual *Oil and Gas Reports* published by the Railroad Commission of Texas.

6.0 CONCLUSIONS

Wyoming produces oil from shoreline barrier deposits from eight formations ranging in age from Cambrian to Cretaceous. These strandline/barriers were deposited along the shores of the Continental Sea and later separated into six basins (Powder River, Green River, Big Horn, Wind River, Shirley, and Hanna). California shoreline barriers formed in 15 formations of Early to Mid-Tertiary age in four distinct basins (San Joaquin, Cuyama, Salinas, and Santa Maria). These basins were separated by mountain ranges and faults throughout and after the period of deposition. The shoreline barriers of Texas are represented by five groups or formations of Cretaceous and Tertiary age. They were deposited in two adjoining basins (East Texas and Texas Gulf Coast), which retained their original relative positions during and since the time of deposition.

The heterogeneity of the strandline/barriers in Wyoming, California, and Texas is similarly affected by the variations in facies relationships found within the barrier deposits. The heterogeneity of the reservoirs is further affected by tectonic movements of and within the basins, and the diagenetic stages of compacton, cementation, clay and detrital pore filling, and dissolution.

Previous research and literature has emphasized facies relationships and environments much more in Wyoming and Texas than in California. These relationships are more readily applied to production problems in Wyoming reservoirs because of the close proximity of outcrops and subsurface facies of the same formations, which allows interpretation of the effects of facies on production.

Information from the TORIS database for Wyoming, California, and Texas and reports of the Wyoming Oil and Gas Conservation Commission and the Texas Railroad Commission give statistics on porosity, permeability, depth, and net pay zones in Tables 2–1 through 4–1. Additional information on depositional environment, water saturation and recovery efficiency is available from Texas in Tables 4–2 through 4–10. Overall averages for fields producing from shoreline barrier deposits show that permeability is highest for California (1,332 mD), moderately high for Texas (995 mD), and low for Wyoming (95 mD). Porosity averages are the same for California and Texas (28%) and 17% for Wyoming. The main causes of these regional differences are the degree of compaction of the sediments and rocks and the diagenetic stages which have affected them.

Original depths of deposition were shallow marine. Subsequent changes are the result of later deposition, tectonic movements (uplift, erosion, and strike-slip movement), subsidence and growth faulting, and when these events occurred (pentecontemporaneously or postdepositionally). The thickness of the pay zones differs from formation to formation and by region. California generally has the thickest pay zones reflecting heavy sediment input into rapidly subsiding basins with restricted lateral extent. The gradual subsidence of both the Continental Sea coast in Wyoming and the Texas Gulf Coast Basin allowed for wider deposition of lateral and vertical stacked strandline/barriers with less thickness at any one location.

Great similarities can be seen in the Class 4 deposits of Wyoming, California, and Texas in reservoir characteristics most affected by facies and original shoreline barrier environment of deposition. The differences appearing when comparing these regions are due to the configuration of the basins, the period of deposition in one location, diagenetic stages, and the tremendous effects of pentecontemporaneous, and postdepositional tectonic movements, and halokenetic tectonics.

7.0 RECOMMENDATIONS

This analysis of the shoreline barrier island deposits of Wyoming, California, and Texas shows how the basinal configuration and tectonics can affect both oil recovery efficiency and research. The Almond Formation in the Greater Green River Basin of Wyoming proves to be an excellent site to continue research because it meets so many of the reseach requirements. The close association of outcrops to similar facies in the subsurface allows for further refinement in analysis of the effects of facies and diagenetic control on heterogeneties and recovery.

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