Korean Jour. of Petrol. Geol., V. 4, No. 1/2, p. 27~39, 1996

A Review of Tectonic, Sedimentologic Framework and Petroleum Geology of the Cretaceous U. S. Gulf Coast Sedimentary Sequence

백악기 미국 걸프만 퇴적층의 지구조적, 퇴적학적, 석유지질학적 고찰

Dae-Kyo Cheong(정대교)

Abstract : In the Cretaceous, the Gulf Coast Basin evolved as a marginal sag basin. Thick clastic and carbonate sequences cover the disturbed and diapirically deformed salt layer. In the Cretaceous the salinities of the Gulf Coast Basin probably matched the Holocene Persian Gulf, as is evidenced by the widespread development of supratidal anhydrite. The major Lower Cretaceous reservoir formations are the Cotton Valley, Hosston, Travis Peak siliciclastics, and Sligo, Trinity (Pine Island, Pearsall, Glen Rose), Edwards, Georgetown/Buda carbonates. Source rocks are down-dip offshore marine shales and marls, and seals are either up-dip shales, dense limestones, or evaporites. During this period, the entire Gulf Basin was a shallow sea which to the end of Cretaceous had been rimmed to the southwest by shallow marine carbonates while fine-grained terrigenous clastics were deposited on the northern and western margins of the basin. The main Upper Cretaceous reservoir groups of the Gulf Coast, which were deposited in the period of a major sea level·rise with the resulting deep water conditions, are Woodbine/Tuscaloosa sands, Austin chalk and carbonates, Taylor and Navarro sandstones. Source rocks are down-dip offshore shales and seals are up-dip shales. Major trap types of the Lower and Upper Cretaceous include salt-related anticlines from low relief pillows to complex salt diapirs. Growth fault structures with rollover anticlines on downthrown fault blocks are significant Gulf Coast traps. Permeability barriers, up-dip pinch-out sand bodies, and unconformity truncations also play a key role in oil exploration from the Cretaceous Gulf Coast reservoirs. The sedimentary sequences of the major Cretaceous reservoir rocks are a good match to the regressional phases on the global sea level curve, suggesting that the Cretaceous Gulf Coast sedimentary stratigraphy relatively well reflects a response to eustatic sea level change throughout its history. Thus, of the three main factors controlling sedimentation (tectonic subsidence, sediment input, and eustatic sea level change) in the Gulf Coast Basin, sea-level ranks first in the period.

Key Words: reservoir, source rock, trap, salt diapir, eustatic sea level

요 약

백악기 당시 미국 걸프만 퇴적분지는 대륙연변부의 색(sag)형 퇴적분지로서의 진화과정을 거치고 있었다. 두꺼운 백악기의 쇄설성과 탄산염 퇴적층은 상승 교란작용을 받은 암염층을 덮고 있다. 당시 걸프만 퇴적분지의 염분도는 넓게 발달하고 있는 초조간대의 경석고 퇴적층의 분포로 보아 현생의 페르시아만 환경과 유사했던 것으로 추정된다. 하부 백악기의 주요 저류암(reservoir)으로는 쇄설성 퇴적암층인 카튼밸리(Cotton Valley), 허스톤(Hosston), 트래비스픽(Travis Peak)층과 탄산염 퇴적암층인 슬리고(Sligo), 트리니티(Trinity) - 파인아일랜드(Pine Island), 피어살(Pearsall), 글랜로스(Glen Rose), 에드워드(Edwards), 조오지타운(Georgetown)/부다(Buda)층이 있다. 이 시기 저류암층에 탄화수소를 공급했던 근원암(source rock)으로는 경사방향 하부(down-dip)에 위치하고 있는 셰일과 이회암층이 꼽히고, 덮개암(seal)은 대개 경사방향 상부(up-dip)에 위치하고 있는 셰일과 치밀한 석회암층, 그리고 증발암으로 보인다. 하부 백악기 동안 전 걸프만 퇴적분지는 천해환경하에 있었는데, 남서부 지역은 백악기 말까지 계속 이어졌던 천해 탄산염 환경이, 북쪽과 서쪽지역에서는 육성기원의 세립질 퇴적물이 주로 집적되는 환경이었다. 상부 백악기동안에는 걸프만 퇴적분지는 주요한 해수면 상승기와 연관되어 비교적 수심이 깊었던 환경하에 있었으며 이 때 형성된 주요 저류암층으로는 우드바인(Woodbine)/투스칼루사(Tuscaloosa) 사암층, 테일러(Taylor)와 나바로(Navarro) 사암층과 오스틴(Austin) 백악 및 탄산염암층이 있다. 이 저류암층에 탄화수소를 공급했던 근원암층으로는 경사방향 하부의 셰일층이, 그리고 덮개암층은 경사방향 상부의 셰일층이 그 역할을 담당했던 것으로 해석된다. 백악기 하부와 상부 퇴적층의 주요 트랩(trap)으로는 완만한 기둥형(pillow)으로부터 복잡한 다이아피어(diapir) 형태의 암염층 관련 배사구조와 하단 단층블록위에 놓여 있으며 롤오버(rollover) 배사구조를 갖는 성장단층이 있다. 투수 장애(permeability barrier), 상부 경사방향으로 첨멸하는 사암체(up-dip pinch-out sand body)와 침식부정합면(unconformity truncation)도 걸프만 석유부존에 중요한 역할을 한 트랩들이다. 백악기의 주요한 저류암층들은 범세계 해수면곡선의 하강시기와 잘 일치하고 있는데 이는 백악기동안 형성된 걸프만의 퇴적층서가 범세계 해수면곡선을 전반적으로 잘 반영하고 있음을 의미한다. 즉 퇴적작용을 주로 지

*Department of Geology, Kangwon National University, Chuncheon, Kangwon, 200-701, Korea(강원대학교, 지질학과)

배하는 세 주요 변수인 지구조적인 분지의 침강운동, 퇴적물의 공급, 해수면 변동요소 중에서 해수면 변동요소가 이 시기동안 가장 중요한 역할을 했음을 의미한다.

주요어 : 저류암, 근원암, 트랩, 암염 다이아피어, 범세계적 해수면 변동

INTRODUCTION

This paper provides a petroleum geological framework to the major Cretaceous oil and gas reservoirs of the Gulf Coast Basin in terms of their tectonic, structural and depositional histories and their relationship to eustatic sea level change. The Cretaceous sedimentary equence of the Gulf Coast Basin may be a final product of an intimate tie among three main controlling factors-sediment input, eustatic sea level change, basement tectonics. The most important factor will be evaluated through this work in which tectonic and depositional histories of the Cretaceous Gulf Coast Basin are reviewed. Data used in this paper is compiled mostly from published papers and unpubished reports of the oil companies.

The Gulf Coast Basin is one of the world's largest hydrocarbon producing areas and is one of the most extensively explored. It is located in a region of divergent tectonics at the outer edge of a series of continental plates, south of the Marathon-Ouachita-Appalachian foldbelts and east of the Laramide thrust belts (Fig. 1). It underlies East Texas, Louisiana, Alabama, Mississippi, the Florida Peninsula, northeastern Mexico and the offshore Gulf of Mexico (Fig. 2).

TECTONIC BACKGROUND

The pre-Cretaceous history of the Gulf Coast prior to and during its initial divergence traced continental collision and divergence, accompanied by marine and continental sediment and volcanic fill (Fig. 3a). This complex record ended with break up of Pangea (Salvador, 1979, 1987).

The Gulf Basin originated as a zone of extension in the Triassic, as Pangea broke up. The first phases of basin developement began when a divergent interior fracture basin formed by the breakup of the supercontinent Pangea in the Early Triassic (Fig. 3a & 3b and Fig.1) (Kingston *et al.*, 1983; Cheong *et al.*, 1992). It resembles the present-day asymmetric rift valleys of East Africa (Kingston *et al.*, 1983). The next phase of basin evolution was characterized by the continuation of continental divergence with subsidence of regional grabens. From the Late Triassic to Early Jurassic (Fig. 3a) basin fill was marked by the deposition of the nonmarine sediment. The basement at the edge of both margins continued to subside and was accompanied by the deposition of further nonmarine sediments, widespread halite accumulation followed by a mix of marine and nonmarine sediments during the Mid Jurassic (Fig. 3b). During the late Mid Jurassic to Early Cretaceous, as the spreading center began to grow, the basin evolved as a margin sag (Fig. 3c). Seaward new layers of oceanic crust formed, while the older ones cooled and subsided. The final phases of the present sag history were the continued subsidence of

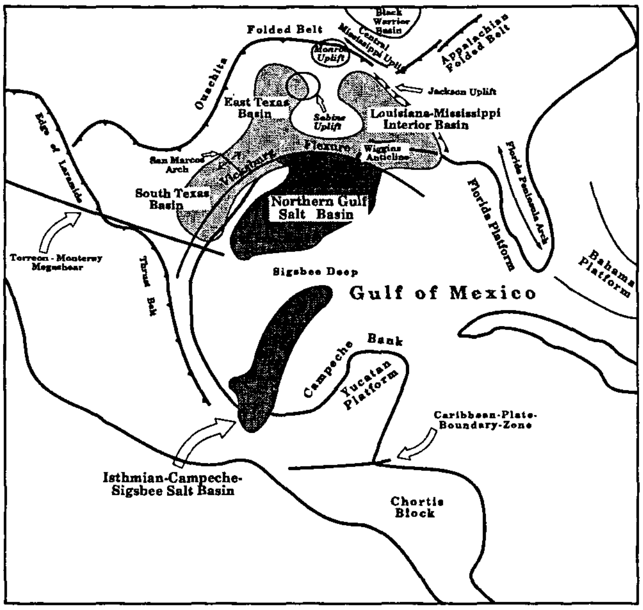

Fig. 1. Shows the prominent geologic features of the Gulf Coast region, including the present distribution of the salt basins, major faults and thrust belts since the Cretaceous (Wood and Walper, 1974; Walper, 1980; Pindell, 1985)

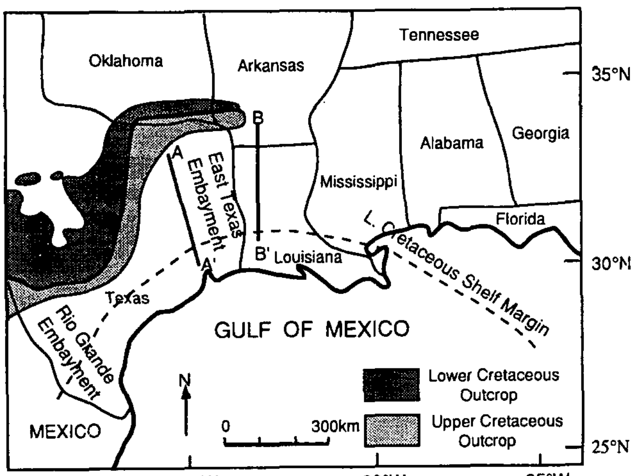

Fig. 2. Location map of the Cretaceous outcrops in the U. S. Gulf Coast Basin. AA' and BB' lines indicates locations of two cross-sections in Figure 5.

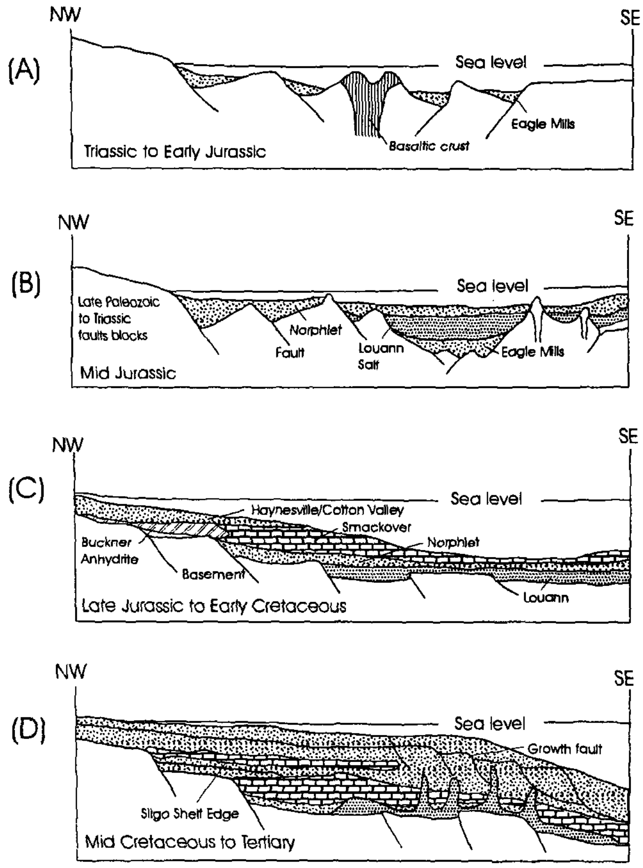

Fig. 3. Evolution of the Gulf Coast Basin from Triassic to Tertiary. (a) Triassic to Early Jurassic, (b) Mid Jurassis, (c) Late Jurassic to Early Cretaceous, (d) Mid Cretaceous to Tertiery.

the continental margin and the deposition of marine sediments including clastics and carbonates. On the open shelf of the Gulf Coast Basin, marine sediments mark periods of highstands of sea, and nonmarine sediments and unconformities mark the lowstands (Galloway, 1989a, b). The continental margins have subsided in response to thermal cooling and sediment loading while salt and mud diapirs have intruded the sediment packages (Fig. 3d). The Late Cretaceous and Cenozoic regional uplift and tectonism in western North America provided large amounts of terrigenous clastic sediments which were transported into the Gulf Coast Basin. Rapid deposition across a shelf underlain by an unstable substrate of salt and/or overpressured mud deposits caused contemporaneous growth faulting.

Buffler *et al.* (1980) divided the evolution of the Gulf Coast Basin into four main tectonic phases: (a) a Triassic 'rift phase' with regional uplift, doming, rifting, and erosion accompanied by filling of a rift basin with continental sediments and volcanics; (b) an Early to Middle Jurassic late 'rift phase' with a medial uplift due to mantle upwelling flnanked by zones of subsidence, and accompanied by incursion of seawater and deposition of thick shallow-water evaporites (i.e. Louann Salt) in the basins on either side of the medial uplift; (c) a Late Jurassic-Early Cretaceous 'drift phase' with seafloor spreading and formation of oceanic crust, accompanied by rapid subsidence of the basin in response to crustal cooling and early deformation due to gravity flowage of salt basinward. This may have been accompanied by deposition of deep water sediments in the central Gulf and shallow water sediments on the adjacent margins. Both facies overlie the salt; and (d) a post- Early Cretaceous 'subsidence phase' in which seafloor spreading ended with major plate reorganization and the continued subsidence of the basin. Deep water sediments collected across the deep basin while carbonate buildups (i.e. Sligo Reef trend), formed along a structural hinge zone at the margins.

Following the Jurassic salt deposition and rifting, plate movement in the Gulf of Mexico ceased in Early Cretaceous (Pindell, 1985). Tectonic activity became thermally driven subsidence accentuated by sediment loading. Most of this subsidence continued along previously established faults (Walper, 1980). The exception to this is some local continental volcanism of the middle to Upper Cretaceous which extended in an arc from the Balcones Fault system through the Magnet Cove, Arkansas to the central Louisiana shelf (Rezak and Tieh, 1984; Ewing and Caran, 1982).

Thinned and rifted transitional crust (6-20 km thick) underlies the southern part of the deep central Gulf and extends to within 100 km of the Campeche escarpment (Buffler *et al.*, 1980). An oceanic crustal layer (5-6 km thick) underlies the rest of the central Gulf (Buffler *et al.*, 1980; Pindell, 1985). Undeformed sedimentary sequences onlap this oceanic crust whereas a disrupted sedimentary cover overlies the disturbed and diapirically deformed salt layer (Buffler *et al.*, 1980). This symmetrical distribution of transitional crust and thick salt on either side of oceanic crust probably reflects how close the evolution of the Gulf of Mexico basin initially matched the north Atlantic in timing, structure, and stratigraphy (Buffler *et al.*, 1980 and Hall *et al.*, 1982).

Lower Cretaceous stratigraphic intervals became more structurally complex, and sedimentation rates and patterns were effected by sediment loading on the underlying Louann Salt. Numerous studies of salt diapirisms and stratigraphic effects of salt movement have been performed for the Gulf Coast (Nettleton, 1934; Parker and McDowell, 1955; Hughes, 1968; Halbouty, 1979; Seni and Jackson, 1983a and 1983b).

DEPOSITIONAL HISTORY

During the Cretaceous, the U. S. Gulf Coast margin continued its evolution as a marginal sag. Initially, major continental drainage in the Early Cretaceous was moved generally northwards and towards the Interior Seaway, but by the Late Cretaceous, the Laramide Orogeny redirected the

Geologic Age	Major Reservoirr Formation	Lithologic Type	Depositional Setting	Geometry & Porosity Type	Seal and Trap	Source	Example and Reference
Lower Cretaceous	Cotton Valley	calcareous sandstone	shallow marine	primary: interparticle	shale and limestone combination: fault and up-dip pinch-out		Diamond, MS Pool Creek, MS (Minihan & Oxley, 1966) Cotton Valley, LA
	Hosston / Travis Peak	sandstone	fluvial and shallow marine	lenticular	shale structural: anticline stratigraphic: up-dip pinch-out		Traurik, TX Opelika, TX Unitesand, MS Athens, LA
	Sligo	limestone: reef, oolitic, skeletal grainstone, sandstone	offshore, shoaling spillover shallow marine platform, reef	elongate primary: interparticle secondary:vuggy, fractured, moldic, intraparticle	shale and limestone stratigraphic: up-dip pinch-out, diagenetic structural: anticline		Black Lake, LA (White & Sawyer; 1968, White; 1972, Bailey; 1978) Sligo, LA
	Trinity, Rodessa, James (GlenRose, and Paluxy)	sandstone limestone: grainstone, mudstone, packstone	shallow marine	secondary: leaching primary: intercrystalline	shale stratigraphic: up-dip pinch-out and unconformity	Monroe Gas rocks	Waveland, MS (Baria, 1981) Sunoco Felda, AL Fairway, TX Talco, TX
	Edwards (McKnight) Georgetown	dolomite limestone	tidal and back-reef, lagoonal	massive secondary: intercrystalline, vuggy, and moldic	anhydrite and limestone stratigraphic: up-dip pinch-out	down-dip shale	JFS, TX (Jacka & Stevenson, 1977)
Upper Cretaceous	Woodbine (Tuscaloosa) Eagle Ford	sandstone: quartzarenite and gluconitic, silty sandstone	shallow marine: offshore barrier and inner shelf	thin lenticular, elongate secondary: moldic, oversized, floating, corroded grain primary: interparticle	shale and limestone combination: fault, dome, anticline and diagenetic and up-dip pinch-out stratigraphic: up-dip pinch-out	up-dip marine shale, down-dip interbedded shale Eaglewood Formation	Kurten, TX (Turner & Conger, 1981) East Texas, TX McComb and Little Creek (Hamlin & Camaroři, 1987) Port Hudson, TX
	Austin Taylor	sandstone: glauconitic, calcareous chalk	shallow marine: offshore barrier and shoaling-up	linear and lenticular	shale structural: anticline with fault	down-dip Ozan Sand	Pendleton Many, LA Giddings, TX Big Wells, TX (Layden, 1971) A.W.P. Olmos (Dennis, 1987)

Fig. 4. Major Cretaceous reservoir groups and their characteristics of the Gulf Coast Basin.

drainage systems towards the Gulf so that clastics overwhelmed the carbonates by the Early Tertiary (Fig. 3c & d) (Wood and Walper, 1974). The general Cretaceous pattern of sedimentation parallels a first order rise in sea level for the Lower Cretaceous with carbonate production and a first order fall in sea level for the Upper Cretaceous with clastic sedimentation.

In ascending order the major Lower to middle Cretaceous reservoir units of the Gulf Coast are the Cotton Valley, Hosston/Travis Peak, Sligo/Pettet, Trinity Group composed of Pine Island, James, and Rodessa, Glen Rose, Paluxy, Fredericksburg Group composed of Edwards, McKnight, and Washita Group composed of the upper Stuart City, Georgetown and Buda Formations. During the Lower Cretaceous, the Gulf of Mexico basin was rimmed by extensive carbonate banks which lined most of the present Yucatan Peninsula, northern Cuba, Folorida, and the Bahamas (Paine and Meyerhoff, 1970). Anhydrite occurs updip of the carbonate banks, as they do in the Holocene Persian/Arabian Gulf (Paine and Meyerhoff, 1970).

By the middle Cretaceous, San Marcos Arch, Sabine Uplift, Monroe and Jackson Uplifts (Fig. 1) exerted an important influence on the course of subsequent sedimentation along the Gulf Coast, particularly during the Late Cretaceous (Paine and Meyerhoff, 1970; Anderson, 1979). A middle to Upper Cretaceous marine transgression occurred in the Gulf Coast Basin which coincided with local subsidence and formation of the Mississippi, Rio Grande, Tampico, and Isthmus-Macuspana embayments that later became chutes for Tertiary and Quaternary sediments (Rainwater, 1967). Some of the major hydrocarbon fields for the Gulf Coast Cretaceous section are listed in Fig. 4 and regional cross-sections of their stratigraphy in Fig. 5.

Lower to middle Cretaceous

During the Valanginian the lower Hosston was deposited during a sea level drop and the middle and upper Hosston was deposited during a subsequent sea-level rise which ended in the middle Barremian (Haq *et al.*, 1987). The lower Hosston carbonates and clastics of the Valanginian lowstand have been documented in East Texas (Fig. 5) (Finneran *et al.*, 1984) and North Louisiana (Coleman and Coleman, 1981). In South Texas the Hosston is composed of tidal flat dolomites interfingering with supratidal to subtidal carbonates (Bebout *et al.*, 1981). Moving into East Texas, the Hosston/Travis Peak was formed by large prograding fan delta systems capped by shallow marine facies (McGowen and Harris, 1984; Tye, 1989). Eastward in the Mississippi Salt Basin three prograding deltaic lobes were recognized (Reese, 1976). In the western Gulf Coast the upper Hosston interfingers downdip with and is onlapped by the Sligo shelf and shelf margin carbonates (Bebout *et al.*, 1981) and passes eastward into the Sligo clastics.

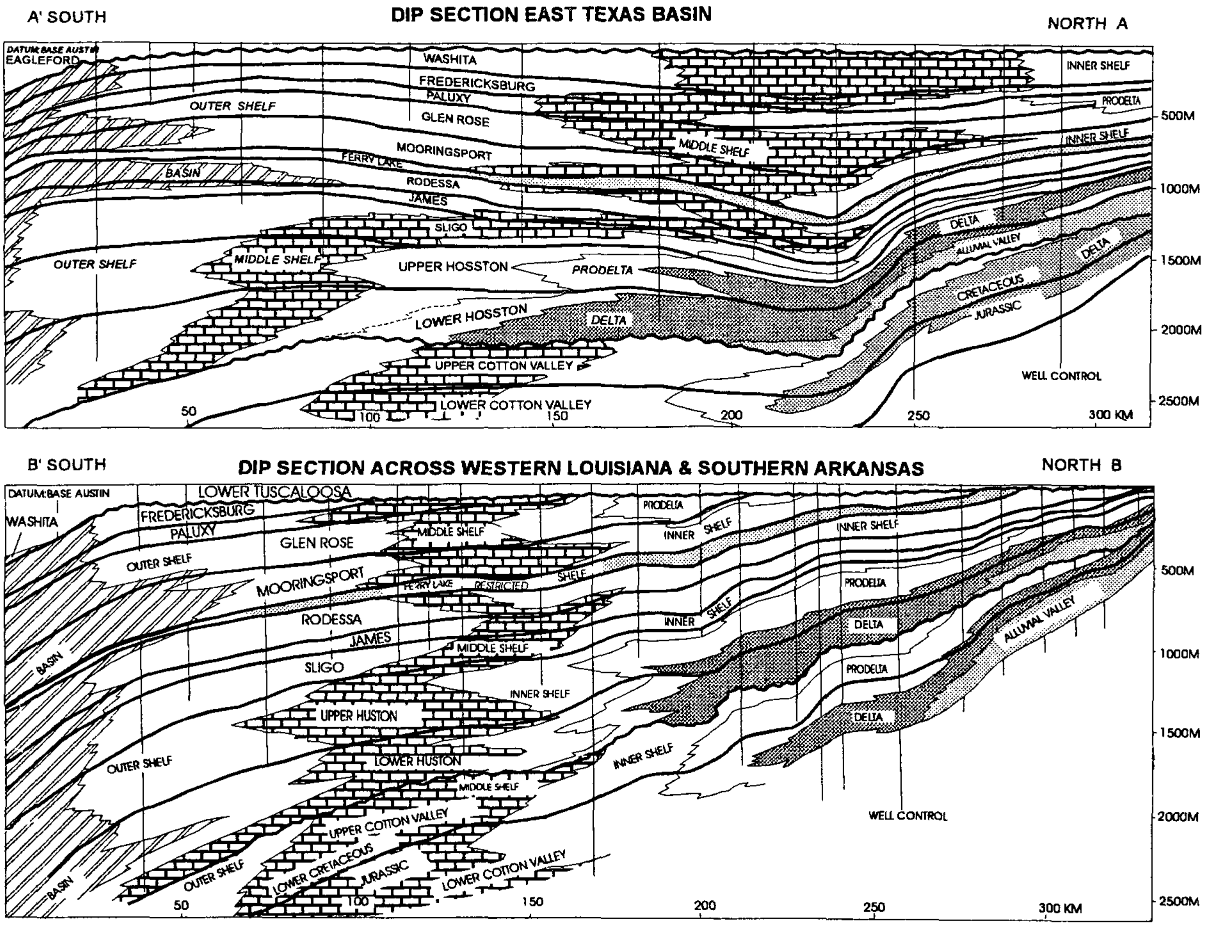

Fig. 5. Jurassic and Lower to Middle Cretaceous cross-sections of the Gulf Coast (From McFarlan, Jr., 1981). The locations of two sections are shown in Figure 2

Lowstand fluvial sedimentation in the Hosston Formation ended with a major sea-level rise and the deposition of a transgressive shallow marine facies which consists of interbedded very fine- to fine- sandstone, grey mudstone, and sandy fossiliferous oolitic limestone (McGowen and Harris, 1984). The Sligo/Pettet Formation onlaps and is laterally equivalent to the clastic sediments of the Hosston Formation. It is capped by the Pearsall Formation in South Texas and by the Pine Island Formation in Arkansas and Louisiana. During the Sligo deposition, reefs and shelf margin carbonates developed along a hingeline following a broad trend from South Texas (Bebout *et al.*, 1981) through Louisiana (Hermann, 1971). In South Texas, inner shelf lagoon mudstones, oolitic shoal grainstones, coralgal biohermal boundstones, and caprinid biohermal rudstones are reported through the Sligo core studies (Bebout *et al.*, 1981). Over the Louisiana portion of the Sligo hingeline, the reef trend coincides with the separation between the North Louisiana synclinal salt basin and the South Louisiana salt basin (Hermann, 1971). As in South Texas, the principal frame builders of the Sligo reef were caprinids and algae, and the reef core was formed by a caprinid biosparite (Herrmann, 1971). In central Louisiana and South Texas, Herrmann(1971) and Bebout *et al.* (1981) respectively suggested that the Sligo limestone accumulated on shallow shelf and shelf margin, transitional between deltaic settings of the Hosston updip and basinal marine setting of the Hosston downdip. We suggest that the Sligo represents deposition during a general highstand of eustatic sea level in the late Barremian and early Aptian (Haq *et al.*, 1987) (Fig. 6).

In the Gulf Coast the Lower Cretaceous Nuevo Leon Group consists, in ascending order, of the Sligo, Pettet/Hosston, Travis Peak Formations, and the Trinity Group consisting of the Peasall and Glen Rose Formations (Fig. 5, Fig. 6). The Pearsall Formation lies directly on the Sligo and it's base is the lateral equivalent of the Pine Island Formation and the James Limestone. The Pine Island Formation and the basal portion of the Pearsall were deposited upon an erosional unconformity created during a sea-level lowstand (Haq *et al.*, 1987; Scott *et al.*, 1988). In South Texas, this Pearsall facies accumulated in two depositional settings: a high-energy carbonate shoal of porous grainstones and boundstones, and a low-energy open shallow shelf of non-

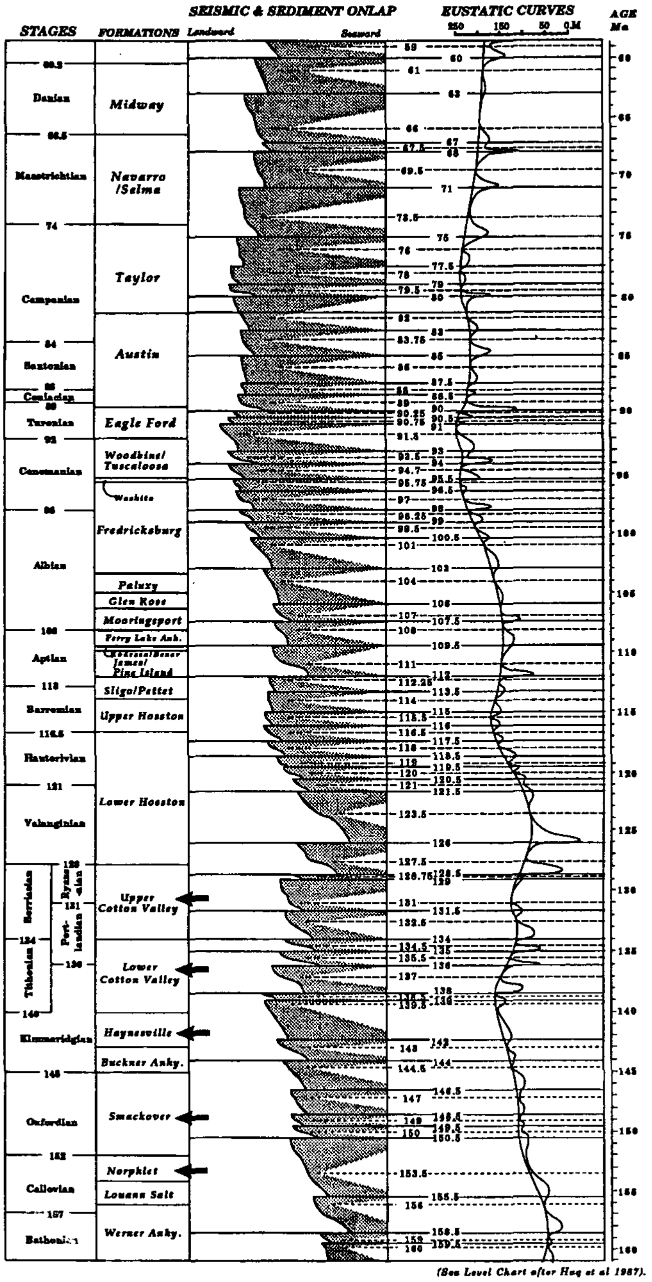

Fig. 6. Upper Jurassic and Cretaceous chronostratigraphic section of West Louisiana, major hydrocarbon occurrence, and cycles of sea-level change. The arrows indicate the Jurassic and Lower Cretaceous formations which contain major reservoir rocks (Compiled from McFarlan, Jr., 1981; Galloway, 1989a, b; Evans, 1987; Haq *et al.*, 1987; Cheong *et al.*, 1992).

porous low-energy packstones and wackestones (Loucks, 1981). Moving to East Texas, the James Limestone being a partial equivalent of the Pearsall in South Texas is composed of updip quartzose sandstones and hydrozoan stromatolites, rudist boundstones, skeletal grainstones in a downdip carbonate complex (Achauer, 1985). Similar James facies are found throughout Louisiana (Hermann, 1976) and Mississippi (Stoudt, personal communication). Overlying the Pearsall-James units, the Rodessa/Bexar are the transgressive and highstand system tracts deposited during a subsequent sea-level high in the Aptian (Haq *et al.*, 1987; Scott *et al.*, 1988).

The Glen Rose Group, overlies in South Texas, interfingers as in East Texas with the Pearsall, and is the age equivalent to the downdip Stuart City Formation which is a reef trend (Bebout *et al.*, 1981; Galloway *et al.*, 1982; Tyler *et al.*, 1985). In South Texas, the Glen Rose Group is separated into upper and lower members by a lagoonal bed containing the Corbula bivalves; a small clam which tolerated highly saline water (Stricklin and Amsbury, 1974). The lower Glen Rose of South Texas is the age equivalent of the Rodessa Formation of the East Texas Basin and Louisiana/Mississippi Salt Basins. In South Texas, the lo `wer Glen Rose was deposited in a high-energy rudist reef and grainstone carbonate complex which prograded over deeper water, low-energy lime mudstones forming a low relief carbonate ramp (Bay, 1977). During the deposition of this unit, sea-level rise kept pace with the sedimentation of the biohermal rudist facies (Bay, 1977). The lowermost part of the upper Glen Rose is composed of evaporite stringers which are interbedded with the Corbula bed and its restricted marine facies (Bay, 1977).

Passing into East Texas, the Rodessa Formation equivalent to the lower Glen Rose is made up of mixed continental red beds and quartzose sandstones, and is prograding downdip into nearshore and shallow-shelf marine skeletal grainstones with localized coralgal patch reefs (Bushaw, 1968). The Rodessa in Louisiana has similar facies to East Texas which becomes more siliciclastic prone eastwards into the deltaic/marginal marine clastics of Mississippi and Alabama.

By the late Rodessa time throughout the Gulf Coast, a nearly complete restriction of the Lower Cretaceous shelf occurred. These restricted to semi-restricted environments lead to shallow, hypersaline lagoonal deposits of gypsum, algal mats, and intertidal shoals (Loucks and Longman, 1985). The lagoons were barred from the open sea by downdip rudist bank packstones and grainstones which occurred on a structural sill (Loucks and Longman, 1985). These subsurface anhydrite and carbonates are the Ferry Lake Anhydrite.

By the Barremian-Aptian upper Glen Rose time in South Texas, the prograding high-energy carbonate complex had evolved into a carbonate shelf with a marked topographic break in slope (Bay, 1977). These South Texas calcareous clays, dolomites, and limestones have been described by numerous authors (Stricklin *et al.*, 1971; Lozo and Smith, 1964). Subsurface shelf-edge reef deposits of the upper Glen Rose have been reported in East Texas and Louisiana (McNomee, 1969). In addition, the upper Glen Rose equivalents to the Mooringsport Formation in Mississippi have been described as updip paralic clastics to downdip lagoonal and backreef miloid and orlictolinid wackestones and grainstones through rudist bioherms and reefs on the shelf edge (Baria, 1981).

The Glen Rose carbonates of the Trinity Group in South Texas were displaced by clastics of the Paluxy Formation in a minor regression (Lozo and Smith, 1964; Rose, 1972). In East Texas, as well as the remainder of the eastern Gulf Coast a major regression was occurring with the deposition of the Paluxy Formation. The Paluxy is composed of sandstones and shales which were derived from a northerly source in the East Texas Basin (Caughey, 1977) and from the flanks of the Central Texas Platform (Bay, 1977). These East Texas sandstones were deposited in fluvial-deltaic, strandplain, lagoonal, coastal barrier environments interfingering with shelf marls and carbonates (Caughey, 1977). Similar facies can be inferred for Paluxy sandstones to east in Mississippi (Reese, 1975). A correlation chart (Rose, 1972) suggests that these sandstones were deposited on an erosional unconformity cutting into the underlying Glen Rose. At the same time, laterally and to the southwest carbonates accumulated on the southern portion of the Central Texas Platform (i.e. San Marcos Platform). We believe the Paluxy sedimentation occurred during a sea-level low in the mid Albian (about 103 m.y. on the Haq *et al.*' (1987) curve).

Following the Paluxy deposition, the Fredericksburg and lower Washita Formations accumulated in evaporitic and shallow marine environments (Bay, 1977) while the shelf margin Stuart City reef continued to aggrade and prograde in a downdip position. Locally in Texas, the upper Glen Rose, known as the Edwards, is made up of high-energy shelf margin carbonates. These coral-caprinid rudist and requenid rudist boundstones and rudist grainstones are deposited in a complex of reefs, banks, bars, and islands (Bebout, 1974). In the Stuart City or Edwards time reef trend developed as an almost continuous barrier around the ancestral Gulf of Mexico during the Fredericksburg and part of Washita time on a well-defined shelf margin (Bay, 1977; Winker and Buffler, 1988).

Over in the East Texas Basin, the landward equivalent of the Edwards reef trend is in a shelf embayment (Bay, 1977) composed of nodular limestones and wackestones with mollusks and ammonites. Moving updip onto the Central Texas Platform, it is flanked by rudist bioherms and carbonate grainstones and capped by carbonate mudstones and evaporites. These sediments were deposited in evaporitic lagoons and supratidal flats of the Kirschberg Evaporite (Fisher and Rodda, 1969; Rose, 1972). Moving further to southwest in South Texas the Kirschberg Evaporites pass into additional high-energy rudstones and grainstones which are equivalent to calcareous mudstones and evaporites of the Maverick Basin's McKnight Formation (Rose, 1972; Bay, 1977; Miller, 1984). The McKnight Formation is interpreted to be deposited in restricted, euxinic waters (Bay, 1977).

Carbonates are the dominant rock type in the Texas and Louisiana portion of the Fredericksburg, whereas large siliciclastic, deltaic systems were active further east in Mississippi (McFarlan, 1981). Downdip from the depocenters gray shales, limestones and fine-grained siliciclastics were deposited on a shallow marine shelf (Rainwater, 1970; Reese, 1975).

During the Fredericksburg, Rose(1972) stated that the rate of subsidence was probably balanced with the rate of sea-level rise. Following Rose(1972), that the end of Fredericksburg deposition coincides with the increase in the frequency of the sea level fluctuations in the Albian. The Edwards reef trend of the Gulf Coast was eventually drawn at the end of Washita time with a sea level rise during deposition of the Georgetown and Del Rio Formations and other laterlly equivalent Washita sediments. The Georgetown sediments are open marine fine-grained limestones with argillaceous streaks and the Del Rio is composed of gray shales.

The sedimentation of the upper Washita culminated with the deposition of a sheet-like lime mudstone called the Buda Limestone (Bay, 1977) which we interpret as co-inciding with the sea level high in the mid Cenomanian on the Haq *et al.* (1987) chart (Fig. 5). It is the first distinctive carbonate unit occurring over the Georgetown and the Del Rio Formations (Siemers, 1978). This rock is a highly bioturbated calcisphere- and echinoid- bearing biomicrite, which was inferred to be deposited in a deep quiet-water slope or basin setting (Siemers, 1978). As these transgressive carbonates and shales were being deposited in the western Gulf Coast, siliciclastics were lain down in the eastern Gulf Coast (Braunstein *et al.*, 1988).

Upper Cretaceous

The Upper Cretaceous sequence comprises the Woodbine/Tuscaloosa, Eagle Ford, Austin, Taylor and Navarro Groups (Fig. 5, Fig. 6). These lithologically variable sequences were deposited during a time of generally high but varying sea level (Haq *et al.*, 1987) and major tectonic events. The sedimentary units as described for the productive Gulf Coast region may not record all of the variations seen on the Haq *et al.* (1987) chart because only the up-dip facies are well known by outcrops and existing subsurface well control (Fig. 6).

Middle Cretaceous deposition ended with an influx of siliciclastic sediments of the Woodbine and Tuscaloosa

Groups. This coincides with a sea-level low which followed the 98 Ma sea-level highstand on the Haq *et al.* (1987) chart. The sea-level low caused truncation of the underlying Lower Cretaceous sediments which are widely recognized in the Gulf Coast area. It is recognized that the Woodbine of East Texas correlates with the Tuscaloosa Formation of Louisiana to Alabama and may be lithostratigraphic equivalent, but may not represent the same depositional system (Oliver, 1971). Changes in tectonism at the source area resulted in significant variation on the depositional systems.

No sand equivalents of Woodbine or Tuscaloosa age are recognized in South Texas, however in East Texas and the remainder of the Gulf Coast, these siliciclastics have been one of the most sought-of-the reservoirs. The East Texas updip Woodbine has been well-documented by Oliver(1971) as a deltaic system with abundant nearshore marine or destructional deltaic deposits. It has also been subdivided into a lower sequence of wave-dominated deltaics, being the Dexter equivalent, and a overlying sequence of fluvial to strandplain coastal barrier facies deposited as the Lewisville equivalent by wave-dominated deltaics (Tyler *et al.*, 1985). The source of these siliciclastics come from the exposed Paleozoic section of the Ouachita Mountains of Oklahoma and Arkansas and from the Lower Cretaceous section being eroded on the Sabine Uplift. Passing into North Louisiana and the southeastern parts of Mississippi (Funkhouser *et al.*, 1981) and Alabama (Mancini and Payton, 1981). Woodbine/ Tuscaloosa equivalents appear generally to be of a fluvial to destructional deltaic origin deposited on the underlying Cretaceous shelf.

The East Texas coastal barrier and deltaic system may have prograded to near the edge of the continental shelf in the area south of the Sabine Uplift (Siemers, 1978). A short length of these deposits reflects a mud-dominated clastic wedge which has been interpreted as a series of prograding submarine fan lobes (Siemers, 1978). The sediments was channeled from the updip deltaics and near-shore clastics across the narrow shelf through shelf-edge breaks to be deposited downslope of the underlying Early Cretaceous Comanche barrier reef trend (Siemers, 1978). These downdip clastics are deposited via turbidity or submarine density currents in prograding submarine fan lobes (Siemers, 1978). Laterally into South Louisiana, along the same shelf-edge trend, two distributary systems prograded across a bank edge depositing a series of deltaic lobes on the fan bank side (Funkhouser *et al.*, 1981). Growth faults expanded the stratigraphic section and localized the sand development in shallow water condition from deltaic to nearshore marine (Funkhouser *et al.*, 1981) in central South Louisiana. Comparing East Texas with South Louisiana, it is recognized that prograding sequences of sand-rich clastics in South Louisiana were deposited in both shallow- and deep-water environments which form the Woodbine/Tuscaloosa clastic wedge (Smith, 1985).

The progradation of siliciclastics continued till the source of clastics was terminated by a sea level rise which coincided with deposition of the transgressive Rapides shale. Siemers (1978) noted that there is no unconformity between Rapides shale and the overlying Austin Chalk in a basinal or forereef position. As Siemers (1978) indicated, the sediment sources were cut off and subsequent deposition of the Austin occurred.

The upper Woodbine, Eagle Ford, Rapides, and Austin Chalk, described by Siemers (1978), represent a lowstand shelf margin wedge capped by a transgressive shale followed by a highstand carbonate. This does not account for all the fluctuations seen on the Haq *et al.*' (1987) chart. Some variations may be apparently missing since the section was thinned through onlap onto the shelf.

The Austin transgression that inundated all of Texas ultimately onlapped the Monroe Uplift and the South Arkansas highland (Nichols, 1964). Deposition of the Austin Chalk was controlled by paleobathymetric variations resulting in accumulation of argillaceous chalk in shallower water grading basinward into deeper water argillaceous limestones (Dravis, 1979). The Austin Chalk is an open-marine, foraminifera and coccolith-bearing micrite (Scholle, 1977). The Haq *et al.*' (1987) chart indicates that the Austin Chalk was deposited during a second order sea-level low in possibly from the latest Turonian through Coniacian to Santonian. However, it is our contention that the Austin Chalk was deposited on a deep shelf drowned by a major rise in sea level. Sediment starvation, induced by the depth of water, produced a wedge of carbonates, cut off from the distant updip clastics. The resulting starved chalks lay in a topographically low position but onlapped the downdip Eagle Ford.

Outside of South Texas, limestone deposition was interrupted by pulses of clastic deposition which have been interpreted to be littoral to sublittoral deposits in Arkansas and Louisiana (Dolloff *et al.*, 1967) and open marine shelf environments in Alabama (Mancini, 1985).

During deposition of the chalks and marls of the upper Austin and lower Taylor Groups, volcanic activity was reaching a peak in the Gulf Coast (Ewing and Caran, 1982). Tuff mounds formed by accumulation of volcanic ash on seafloor around submarine volcanic vents became subsequent reservoirs themselves as well as localizing deposition of shoal-water carbonates (Ewing and Caran, 1982). Volcanic clastic sequences have been noted in formations from the Albanian Del Rio Clay to the Maestrichtian Navarro Group (Baldwin and Adams, 1971).

The Tayler and Navarro Groups were deposited disconformably on the Austin volcanics, carbonates and siliciclastics, and its equivalents. The Taylor Group of South Texas consists of the lower reworked carbonate grainstones forming atoll reefs around volcanic seamounts (known as the Anacacho Lime) and the overlying reworked fluvial siliciclastics of wave-dominated deltaics of the San Miguel Formation (Tyler *et al.*, 1986). In the remainder of the Gulf Coast shallow water marine clastics and neritic limestones and marls are predominent (Dolloff *et al.*, 1967; Holcomb, 1971).

In the Navarro Group, reeflike carbonate rocks are developed on the Monroe and Kackson uplifts, although the Navarro Groups is primalily a siliciclastic sequence in the Gulf Coast region (Holcomb, 1971). The Navarro clastics in the central Gulf Coast are interpreted to be deposited in sublittoral, littoral to neritic environments (Dolloff *et al.*, 1967). In South Texas, the Navarro Group is composed of the siliciclastic Olmos Formation and Escondido Formation. The Olmos is interpreted as fluvial- to wave- dominated deltaics with thin transgressive sandstones which formed as progradational depocenters foundered (Indest and McPherson, 1985). In contrast, the Escondido siliciclastics were deposited in a coastal lagoon, bay and barrier bar complex (Cooper, 1970).

In summary, the Taylor and Navarro Groups are mixed carbonates and clastics which become dominantly clastic upward, and accumulated on the shelf during a series of sea level fluctuations in the Campanian and Maastrichtian (Nichols, 1964). In general, the carbonate units of chalks and marls were deposited during sea-level highs, and the clastic units of deltaic to shallow marine and offshore barrier bar facies were deposited during intervening sea-level lows. The stratigraphy relects a second order sea-level drop to the begining of the Tertiary and Wilcox siliciclastic deposition.

HYDROCARBON OCCURRENCE

Lower Cretaceous

Oil and gas occurs throughout the many Lower Cretaceous formations - Cotton Valley, Hosston/Travis Peak, Sligo, Rodessa, James, Glen Rose, Paluxy, Edwards, McKnight, and Georgetown (Fig. 4), but the Cotton Valley and Hosston/Travis Peak clastic are the most prolific formations. The age ranges of major Lower Cretaceous reservoir rocks are generally well-matched to the regressional phases of the Haq's(1987) global sea level curve. This suggests that eustatic sea level changes played a major role in controlling the sedimentary character of the Gulf Coast sedimentary record and the development of the reservoirs.

The lowermost Cretaceous reservoir is the Cotton Valley sandstones which were deposited in shallow marine setting, such as the Pool Creek field in Mississippi (Minihan and Oxley, 1966). The seals of the Cotton Valley hydrocarbon play are shales and limestones. The main porosity type is primary interparticle. Combinations of faults and updip sandstone pinch-outs form major traps.

The fluvial-deltaic Lower Cretaceous Travis Peak Formation forms the Chapel Hill field in East Texas, and is equivalent to the Hosston Formation of Louisiana, Arkansas, and Mississippi, which produces gas and oil on the western flank of the Sabine Uplift (Dutton *et al.*, 1987). The Hosston/Travis Peak reservoirs are fluvial and shallow marine lenticular sandstones. Interbedded shales are seals, anticlines and updip sandstone pinch-outs are traps.

Most discoveries from the shallow Cretaceous carbonates in South Texas have been in the Sligo, Glen Rose, Paluxy, and Austin Chalk Formations (Loucks, 1981). The Pearsall Formation was thought by Loucks (1981) to have little potential despite their highly porous potential reservoirs and hydrocarbon shows however this may be due to limited exploration in these units. The major limiting factor to hydrocarbon accumulation in these units appears to be an absence of traps at the time of hydrocarbon migration (Loucks, 1981). The Lower Cretaceous carbonate reservoir rocks in the Sligo, Trinity and Edwards Formations of the northern Gulf Coast area (e.g. the Black Lake field and Delhi field in Louisiana, JFS field in Texas, and Waveland field in Mississippi) consist of reef and oolitic and argillaceous carbonate build-up facies of shallow marine, lagoonal, and tidal settings which are associated with folding induced by salt tectonics (Fig. 4) (White, 1972; Powell, 1972; Jacka and Stevenson, 1977; Baria, 1981). The Lower Cretaceous carbonate reservoirs shows various secondary porosity types-vuggy, fractured, moldic, leached, intercrystalline, interparticle. Seal rocks are shales, limestones, and anhydrites. Main traps are stratigraphic-diagenetic and unconformity traps- and salt-related structural.

The shales interbedded with Travis Peak reservoir sandstones contain a low percentage of organic matter whose kerogen type is different from the hydrocarbons of the field, and this suggests these shales are not the source of the oil and gas here (Dutton *et al.*, 1987). Dutton *et al.* (1987) studied the organic geochemistry of the hydrocarbons to identify the source rocks, in combination with stratigraphic and structural information about the Sabine Uplift area. They concluded that there are four possible major source rocks for the Lower Cretaceous: 1) the carbonate mudstones of the Jurassic lower Smackover Formation, 2) the dark basinal shales of the Bossier Formation, 3) the downdip marine shales of the Travis Peak Formation.

Upper Cretaceous

The Upper Cretaceous sandstones of the Woodbine (Tuscaloosa), Eagle Ford, Austin, and Taylor Groups which formed as shallow marine sequences and offshore bar deposits are also important reservoirs, such as the Sabine Chalk field in Louisiana and the Big Well field in Texas (Fig. 4) (Woods, 1963; Layden, 1971). The age ranges of major Cretaceous reservoir rocks are also generally well-matched to the regressional phases of the Haq's(1987) global sea level curve. The main reservoir lithology is linear and elongate shaped quartzarenite. The geometry of reservoirs is linear, elongate, and lenticular. Characteristic porosity types are secondary moldic, oversized, floating, and corroded grains. Salt dome-related normal faults and folds are the main trapping mechanisms, such as the Sabine Chalk field in Louisiana (Layden, 1971). Diagenetic and updip sandstone pinch-outs are minor trap types. Shales and and limestones are seals.

In addition, the Upper Cretaceous source rocks of the Eagleford Formation are characterized by oil-prone kerogen that are also likely to have contributed crude oil to the onshore salt basins (Koons *et al.*, 1974). During periods of global climate warmups and major transgressions anoxic bottom conditions were best developed in intraslope basins, and organic-rich sediments were well-preserved in shale prone source beds.

In fact the depositional history of the Gulf Coast sedimentary sequences is a product of an intimate tie between eustatic sea level changes (Haq *et al.* 1987), subsidence and sediment input (Galloway, 1989a, b). The age ranges of the major Cretaceous reservoir rocks generally match the regressional phases of the Haq *et al.*' s (1987) coastal onlap curves. This suggests that eustatic sea level changes played a major role in controlling the sedimentary character of the Gulf Coast sedimentary record and the development of the reservoirs. Of the three main factors controlling sedimentation (tectonic subsidence, sediment input, and eustatic sea level change) sea-level ranks first.

Summary

1. Since the Pangean supercontinental plate had been rifted and separated at the beginning of the Triassic Period, the phases of the Gulf Coast evolved as: 1) an interior fracture divergent basin formed during the breakup of the supercontinent in the Lower Triassic, 2) a basin filling with nonmarine to marine sediment (including salt) in the Upper Triassic to Lower Jurassic, 3) a marine marginal sag basin with shelfal carbonate and evaporite deposition in the Middle Jurassic to Lower Cretaceous, 4) a continental margin subsidence and marine deposition since the Mid Cretaceous.

2. In the Cretaceous the Gulf Coast basin evolved as a marginal sag basin. Thick disrupted clastic and carbonate sequences cover the disturbed and diapirically deformed salt layer. The major Lower Cretaceous formations are the Cotton Valley, Hosston, Sligo, Pine Island, Pearsall, Glen Rose, Edwards, Georgetown, and Tuscaloosa. The salinity of the Cretaceous Gulf of Mexico matched to the Holocene Persian/Arabian Gulf as is evidenced by the widespread development of the anhydrite on the shelf rimmed by carbonates seaward. During this period, the entire Gulf Basin may have been covered with a shallow sea. The deposition of shallow marine carbonates continued to the end of Cretaceous on the continental shelf of the southeastern basin while fine-grained terrigeneous clastics were deposited on the northern and western margins of the basin. The main Upper Cretaceous groups are Woodbine-Eagleford, Austin, Taylor, and Navarro. The Upper Cretaceous Gulf Coast Basin was dominated by a widespread marine transgression and deep water conditions. Deposition in the south and southwest occurred as a series of seaward prograding sedimentary wedges formed in fluvial coastal plains, delta plain, nearshore marine, shallow marine prodelta shelf, and deep submarine fan lobe settings.

3. Reservoir rocks in the Cretaceous Gulf Coast sequence fall in: (1) the Lower Cretaceous Cotton Valley, Hosston/Travis Peak sandstones group and, Sligo, Trinity, and Edwards carbonate group, and (2) the Upper Cretaceous Woodbine, Eagle Ford, and Taylor sandstone group. Major types of traps include permeability barriers where the up-dip sand and carbonate bodies pinch out, unconformity, diagenetic, and salt dome-related folds and faults. Most seals to sandstone reservoirs consist of shales and carbonates overlying and interbedded with reservoir rock, and major carbonate reservoirs are sealed by evaporites. Hydrocarbon occurrence depends largely on the presence of source beds with an appropriate thermal maturity for both the generation and preservation of the hydrocarbons. The organic-rich carbonate facies of the Upper Jurassic Smackover Formation, marine shales of the Lower Cretaceous Bossier and Travis Peak, and the Upper Cretaceous Eagle Ford Formations, were the main sources of Cretaceous hydrocarbons for the Gulf Coast. During periods of global climate warmups and major transgressions anoxic bottom conditions were best developed in intraslope basins, and organic-rich sediments were well-preserved in shale prone source beds.

4. The age ranges of major Cretaceous reservoir rocks are generally well-matched to the regressional phases of the Haq's (1987) global sea level curve. This suggests that eustatic sea level changes played a major role in controlling the sedimentary character of the Gulf Coast sedimentary record and the development of the reservoirs. Of the three main factors controlling sedimentation (tectonic subsidence, sediment input, and eustatic sea level change) sea-level ranks first.

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Manuscript received April 3, 1996